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Bulletin

of

The Geological Society of America

VOLUME 59 June 1948 NUMBER 6

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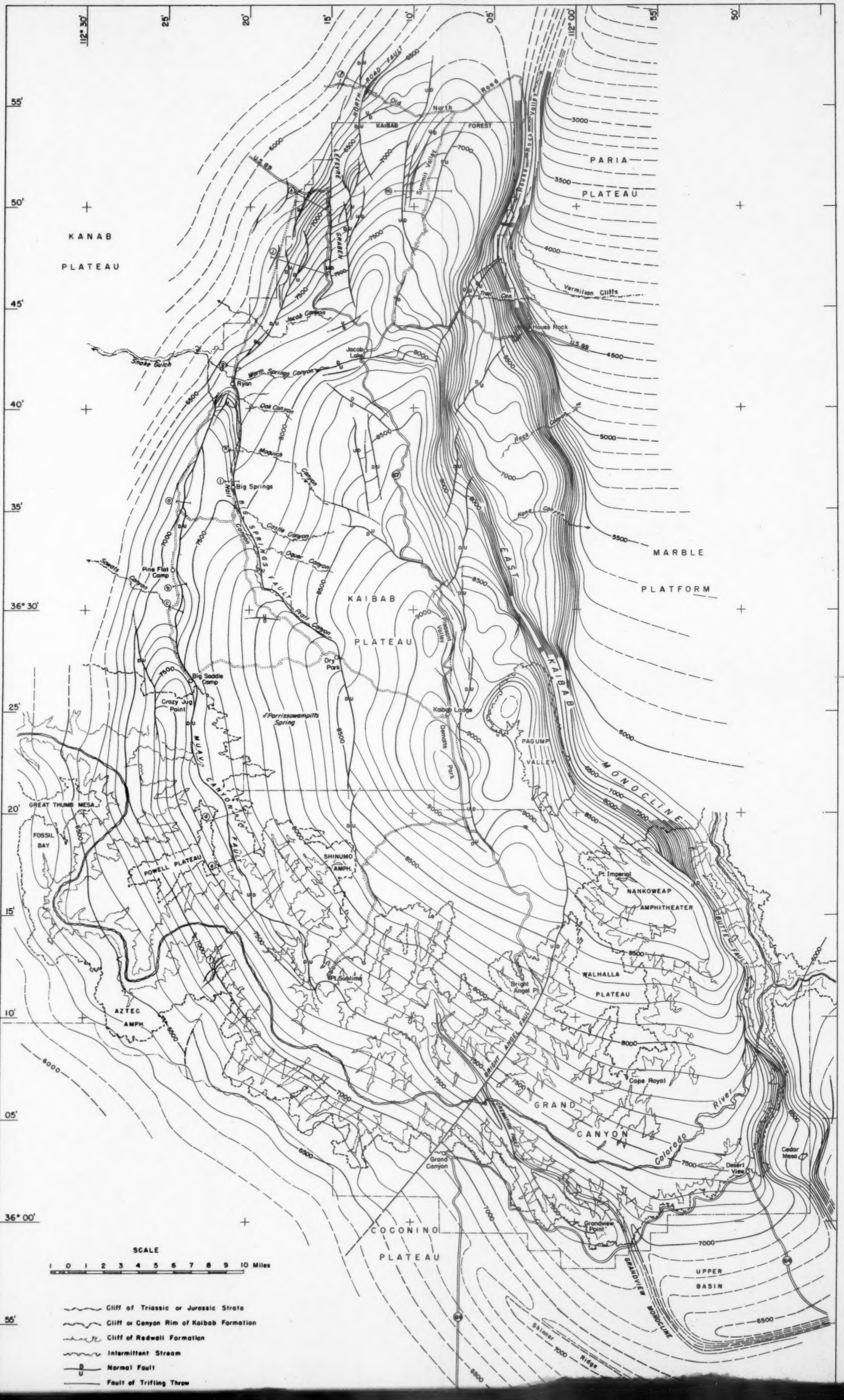
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Desert View
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Shinar Ridge
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1 0 1 2 3 4 5 6 7 8 9 10 Miles
Cliff of Triassic or Jurassic Strata
Cliff or Canyon Rim of Kaibab Formation
Cliff of Redwall Formation
Intermittent Stream
Normal Fault
Fault of Trifling Throw

STRUCTURE CONTOUR MAP OF KAIBAB PLATEAU

Contours approximately on top of Kaibab formation, contour interval 100 feet. Dashed contours unreliable. Numerous trivial dislocations within Grand Canyon are not shown.

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BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
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GEOMORPHOLOGY AND STRUCTURE OF THE WEST KAIBAB FAULT ZONE AND KAIBAB PLATEAU, ARIZONA

BY ARTHUR N. STRAHLER

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ABSTRACT

The western flank of the Kaibab Plateau contains three principal normal faults, all downthrown on the west, and locally developed monoclinal flexures. About half the total displacement of 2500 to 3000 feet between plateau summit and adjacent Kanab platform level is accomplished by these faults and monoclines, the other half by steady westward and northwestward regional dips. Strata on downthrown sides of major fault lines show downbending toward fault planes and indicate sagging of the edge of the lowered plateau blocks during faulting. Numerous minor faults, grabens, and swells affect the plateau arch. All deformational structures of the Kaibab region affecting Paleozoic and Mesozoic strata are regarded as Laramide in age, although positive stratigraphic evidence is completely lacking.

The Kaibab plateau is dissected by numerous resequent and subsequent streams which follow the dip of the resistant, stripped Kaibab limestone or occupy fault lines. Scarps along faults are classified as resequent fault-line scarps, exposed by rapid stripping of weak Triassic shales from the plateau area.

No evidence was found of peneplanation in a former erosion cycle. Small pediment remnants near the lower flanks of the plateau arch are interpreted as local features which do not require regional base-leveling.

The Colorado River in the Kaibab region is explained as subsequent in origin. The ancestral river developed along a belt of weak Triassic shales which formerly encircled the southern end of the plunging Kaibab arch. Later intrenchment into resistant Paleozoic strata and removal of Mesozoic beds from the area have made the canyon appear to cut discordantly across the Kaibab arch.

INTRODUCTION AND ACKNOWLEDGMENTS

The Kaibab Plateau, highest plateau block in the Grand Canyon district, lies between the Grand Canyon and the Arizona-Utah boundary line (Fig. 1). Bounded by the East Kaibab monocline and the West Kaibab fault and monocline zone, the Kaibab Plateau may be visualized in east-west structure section as a keystone among the blocks of the Colorado Plateau province. From the Basin and Range province, 75 miles to the west, a series of fault blocks rises in progressively higher steps to culminate in the western margin of the Kaibab Plateau. From the east, a series of plateau blocks separated by monoclines rises in steps to culminate in the eastern margin of the Kaibab Plateau. Because the western faults are relatively young structures (middle to late Tertiary); and the eastern monoclines are older structures (early Tertiary—Laramide), the Kaibab Plateau is a critical intermediate zone. Interest centers on the West Kaibab fault and monocline zone because it is the last major structure of the Grand Canyon district to be studied in detail. Previous studies by Babenroth and Strahler (1945) seem to indicate that the adjacent East Kaibab Monocline is an early Eocene (Laramide) structure. Koons (1945) concluded that the Toroweap and Sevier faults, adjacent on the west, are possibly late Miocene or early Pliocene. Do the West Kaibab faults and flexures belong to the

western group of younger faults or to the eastern group of older monoclines, or are both ages of deformation represented? These are major questions which the present study attempts to answer. Other problems concern the origin of the Colorado River and its relation to faults and monoclines of different ages, and the evidence concerning a possible Tertiary peneplain, now largely destroyed.

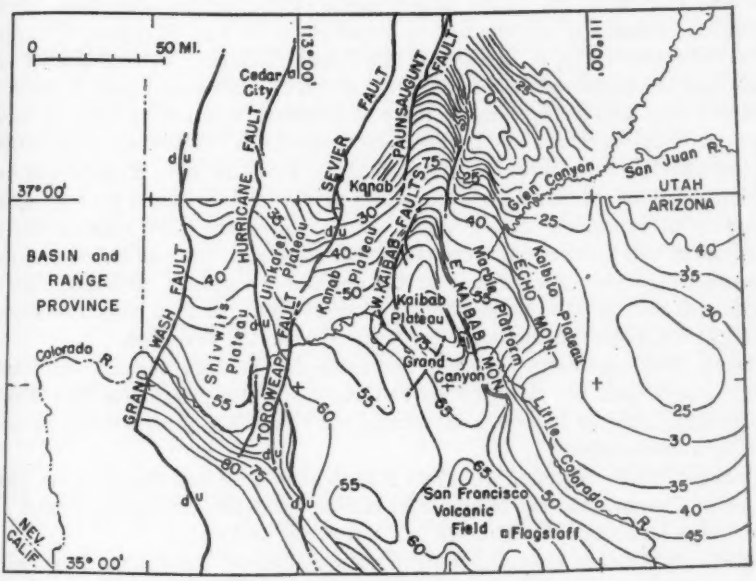

FIGURE 1.—*Index map of Grand Canyon district*

Showing major faults, monoclines, and plateau blocks. Adapted from tectonic map of the United States (Am. Assoc. Petrol. Geol., 1944). Structure contours, labeled in hundreds of feet, are on top of Kaibab formation in Arizona; on top of Chinle formation in Utah.

Field work for this paper was done during the summer of 1946. It was concentrated principally on the West Kaibab fault and monocline zone and on the summit area of the Kaibab Plateau. It adds to structural and geomorphic data previously published on the East Kaibab monocline and Kaibab Plateau (Babenroth and Strahler, 1945; Strahler, 1942; 1944a; 1944b; 1944c).

Funds for the project were supplied from the Penrose Bequest of The Geological Society of America. The writer is especially indebted to Professor Edwin D. McKee, Assistant Director of the Museum of Northern Arizona, for encouragement and assistance throughout the work and for critical reading of the manuscript. Facilities of the Museum, under the direction of Dr. Harold S. Colton, were kindly made available to the writer. Improvements in the manuscript resulted from the critical reading by Professor Claude C. Albritton. Mr. Victor C. Miller served as field assistant.

PREVIOUS WORK

Powell (1875, p. 182–190) first described the principal geological features of the Kaibab region. He named the West Kaibab fault, the Kaibab Plateau, and the East Kaibab fold and concluded that deformation was fairly recent in the regional history. He considered the Colorado River as antecedent to all these structures. Gilbert (1875, p. 51–56) added further details concerning the same area. Dutton made the outstanding contribution to literature on the Kaibab region. His narrative description (1882, p. 122–139) of the Kanab platform, the West Kaibab fault zone, and the Kaibab plateau as he saw them on the trail from Kanab to the north rim of Grand Canyon is a superb piece of literature, noteworthy both for beauty and clarity of description and for accuracy of statement. Elsewhere Dutton (1882, p. 183–186) described three fault lines which comprise the West Kaibab fault zone. Although his description is accurate insofar as it goes, he seems to have overlooked conspicuous monoclinal flexing which locally accompanies the faulting and the presence of two grabens which complicate the structure. He pointed out a curious downbending which affects strata on the downthrown sides of the faults. Dutton considered that the faulting and flexing occurred no earlier than early Pliocene and and that the major drainage lines were antecedent to the structures.

Davis (1901) summarized evidence that monoclinal flexing occurred in the Eocene, much earlier than the older writers had supposed. He placed the West Kaibab faults along with the Toroweap, Hurricane, and Grand Wash faults in a more recent period of deformation.

Johnson (1909) traversed the West Kaibab fault zone and found, in the profile of Jacob Canyon, evidence of an earlier erosion cycle, presumably identifiable with the "Great Denudation" postulated by the previous workers.

Noble (1914) made a detailed study of the southern end of one of the West Kaibab faults which enters the Shinumo quadrangle in Grand Canyon. He found evidence of three displacements along the same fault line: a pre-Cambrian faulting, then a monoclinal flexing with downthrow on the east, and later a normal faulting with the western side downthrown.

Darton (1910; 1923; 1924; 1925) compiled generalized maps showing areal geology, structure, and topography of the Kaibab region. He sketched four "reconnaissance" structure sections (1925, p. 194) across one of the West Kaibab faults.

Babenroth and Strahler (1945) described the East Kaibab monocline. They discussed dating of the monoclinal flexing and origin of the Colorado River, problems closely bound to the present study. A special study of valleys and parks of the Kaibab and their significance in regional geologic history has been made by the writer (Strahler, 1944c).

STRUCTURE CONTOUR MAP

Details of Kaibab Plateau structure are shown by 100-foot structure contours (Pl. 1) drawn approximately on the upper surface of the highest, or Alpha, member of the Kaibab formation (McKee, 1938). The Kaibab Plateau and the Kanab and Marble platforms which adjoin it are vast, stripped structural surfaces underlain

by the Permian Kaibab and Toroweap limestones. Except in Grand Canyon itself and portions of Nail Canyon and Pagump Valley, no older rocks are exposed, nor are there more than a few remnants of the overlying weak Triassic Moenkopi formation. In the field the top of the Beta member of the Kaibab formation was often used for ascertaining structural elevations because it consistently upholds the plateau surface. The upper part of this member consists of massive, resistant sandy limestone beds. The Alpha member which overlies it contains thin limestone beds and much red shale and is therefore missing from large areas, but, where some beds remain, the top of the formation can be determined with reasonable accuracy. Where the Alpha beds are missing the horizon was estimated on the basis of recognizable stratigraphic horizons and the known thickness of the missing series.

Several hundred vertical air photographs which gave complete stereoscopic coverage of the Kaibab region were taken into the field and studied under a portable stereoscope. Even the most trivial structural features are clearly revealed in the photographs. Important places were selected for ground traverses along which structure sections were made and elevations determined.

Elevations were determined by aneroid barometer, checked and rechecked against bench marks within the area. Dr. Harold S. Colton (personal communication) has found from long-continued barometric observations at Flagstaff, Arizona, that air-pressure fluctuations are extremely small during the summer months, despite diurnal temperature changes and frequent thunderstorms. This, too, was the experience of the writer. The recent Jacob Lake quadrangle topographic map (1:62,500) and the Grand Canyon National Park topographic map (1:48,000) provided good control in the central and southern parts of the Kaibab Plateau.

Mapping was further facilitated by a planimetric base map (1:31,680) prepared by the U. S. Forest Service from the air photographs. This map shows drainage lines, roads, section and township boundary lines, and vegetation zones and gives the position and index numbers of all air photographs.

Structure contours of the eastern Grand Canyon adapted from a previously published report (Babenroth and Strahler, 1945), are included in Plate 1 for completeness. More recently published structural details (Van Gundy, 1946) have not been included.

WEST KAIBAB STRUCTURES

GENERAL STATEMENT

The western flank of the Kaibab Plateau has three principal normal faults, locally developed monoclines, and several smaller normal faults (Pl. 1). The three main faults are (1) Muav Canyon fault, (2) Big Springs fault, and (3) the North Road fault. All are downthrown on the west.

MUAV CANYON FAULT

Muav Canyon fault (Figs. 2, 3, Pl. 1), westernmost of the three major West Kaibab faults, extends from Muav Canyon in Grand Canyon northward about 27 miles to a point near Ryan Ranger Station. Throw ranges generally from 150 to 350 feet;

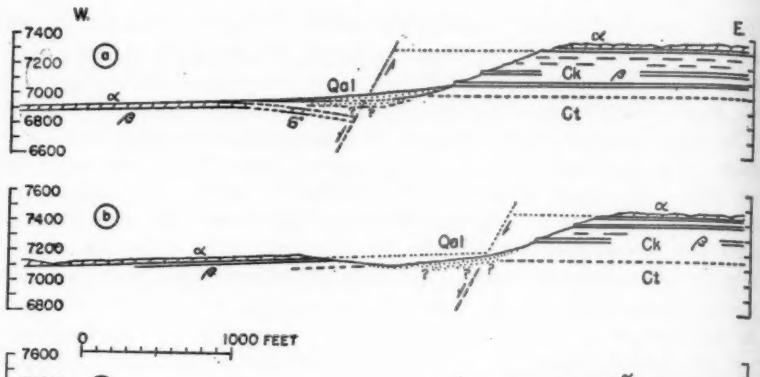

FIGURE 2.—*Structure sections across Muav Canyon fault*

Circled letters (a, b, c) refer to location of sections as shown on Plate 1. Ck—Kaibab formation; α—Alpha member of Kaibab; β—Beta member of Kaibab; Ct—Toroweap formation; Qal—recent alluvium or talus. Exact position and dip of fault not known.

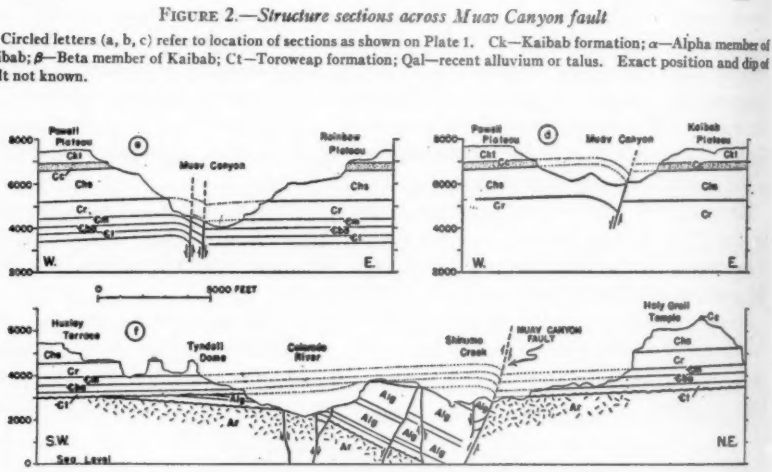

FIGURE 3.—*Structure sections across Muav Canyon fault in Grand Canyon*

Circled letters (d, e, f) refer to location of sections as shown on Plate 1. Sections are copied from L. F. Noble (1915, Pl. 1). Ckt—Kaibab and Toroweap fms.; Cc—Coconino fm.; Chs—Hermit and Supai fms.; Cr.—Redwall fm.; Cm—Muav fm.; Cba—Bright Angel fm.; Ct—Tapeats fm.; Alg—Algonkian sediments; A.—Archean (Vishnu) schist.

the eastern side is downthrown throughout the entire length with the exception of a 5-mile stretch in Muav and Flint canyons, within the Grand Canyon, where the western side is upthrown (Noble, 1914). From the point where it intersects the rim of Grand Canyon near Big Saddle Hunting Camp, the fault cuts southward through the saddle between Powell Plateau and the Kaibab Plateau. After following Muav and Flint canyons for several miles, it passes through a saddle between

Sagittarius Ridge and Point Sublime, dying out within the amphitheater immediately southwest of the latter point. That part of the fault within the Grand Canyon was studied and mapped by Noble (1914) whose data have been employed in the present paper with virtually no modifications. No connection seems to exist between this fault and the line of the Grandview monocline and Cremation fault (Babenroth and Strahler, 1945). The ends of the two structures, although approximately parallel in orientation, are not aligned (Pl. 1).

The Muav Canyon fault, like others in this region, shows a marked downbending of beds on the downthrown side of the fault but no noticeable bending of strata on the upthrown side.

Near the Grand Canyon rim, about 2 miles west of the Muav Canyon fault and striking parallel with it, is a shorter fault with a throw of 200 to 400 feet. Like the Muav Canyon fault, it is downthrown on the west and is one of the series of structures which steps down the strata on the west side of the Kaibab arch.

BIG SPRINGS FAULT

East of the Muav Canyon fault lies the Big Springs fault (Figs. 4, 5; Pl. 1), which also trends north and has marked downbendings of the strata on the western, downthrown side. The Big Springs fault, the principal fault of the West Kaibab group, and the most conspicuous topographically (Pl. 2, figs. 1, 2), is about 40 miles long and has a displacement of 200 to over 1000 feet throughout most of its length. At its northern end, near U. S. Highway 89 (Pl. 1), the Big Springs fault gives way to a monocline with only minor faulting. The monocline causes displacement of approximately 1000 feet and is obliquely truncated at its northern end by a complex graben structure (Fig. 6).

Traced southward from its monoclinal portion, the Big Springs fault becomes a single, simple normal fault striking about S.40° W. to a point near Ryan Ranger Station. Here the fault line turns sharply south and runs through Big Springs Ranger Station (Fig. 7). At the mouth of Pratt Canyon, 5½ miles south of Big Springs, the fault takes an extremely sharp bend to the southeast, following Pratt Canyon to Dry Park Ranger Station. Here the fault again turns sharply south, continuing with diminishing throw past the head of Shinumo Amphitheater, to a point near the Grand Canyon rim in one of the extensions of Hindu Amphitheater (Pl. 1).

Sharp updrag of beds on the downthrow side of the Big Springs fault is clearly revealed in masses of limestone immediately adjacent to the fault on the east side of Nail Canyon (Fig. 4). Westward dips as high as 54° were measured in this drag zone. Elsewhere, however, drag was not seen, perhaps because bedrock immediately adjacent to the faults is usually covered.

NORTH ROAD FAULT AND LE FEVRE GRABEN

Between U. S. Highway 89 and the northermost boundary of the Kaibab Forest lies a complex structure, the Le Fevre graben, striking almost due north and intersecting obliquely the general trend of the main West Kaibab structures (Pl. 1).

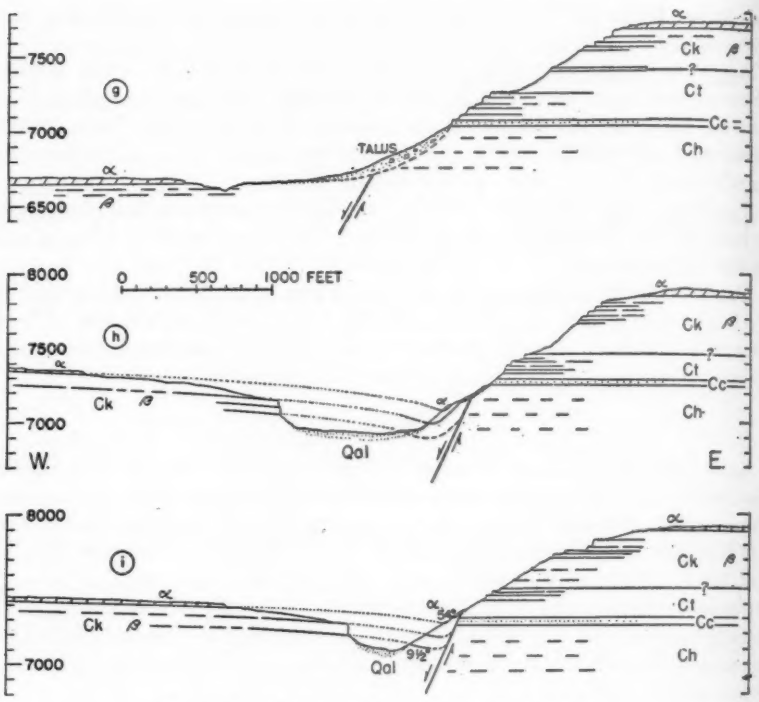

FIGURE 4.—*Structure sections across Big Springs fault*

Circled letters (g, h, i) refer to location of sections as shown on Plate 1. Ck—Kaibab formation; α-Alpha member of Kaibab; β—Beta member of Kaibab; Ct—Toroweap formation; Cc—Coconino formation; Ch—Hermit formation; Qal—recent alluvium. Figures give amount of dip.

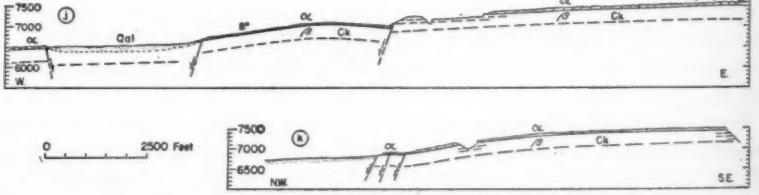

FIGURE 5.—*Structure sections across monocline near U. S. Highway 89*

Circled letters (j, k) refer to positions of sections as shown on Plate 1. Ck—Kaibab formation; α—Alpha member of Kaibab; β—Beta Member of Kaibab; Qal—recent alluvium.

The western bounding fault of the graben is a single straight normal fault with a displacement of 200–250 feet. The eastern side of the graben consists of a number of small faults between which lie north-sloping blocks. The northernmost of these faults, the North Road fault, bends to a northeasterly strike near the northern

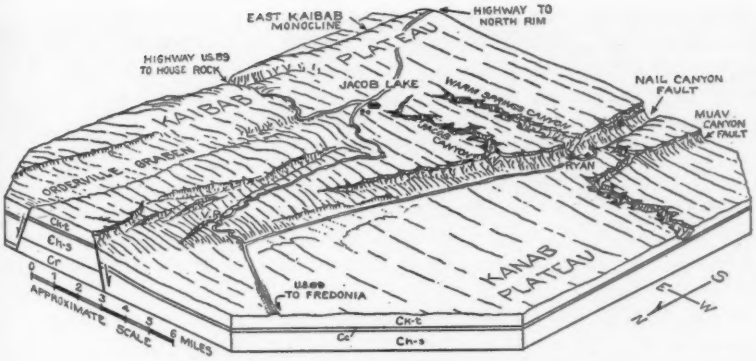

FIGURE 6.—*Block diagram of West Kaibab structures near Ryan*

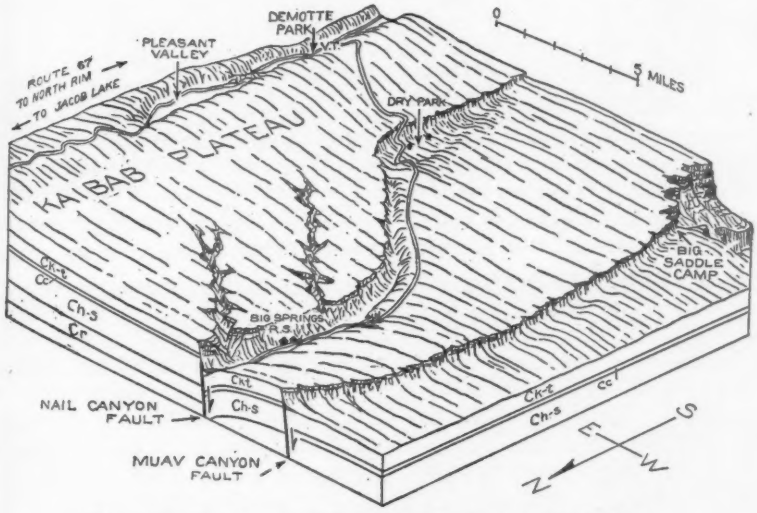

FIGURE 7.—*Block diagram of West Kaibab structures near Big Springs*

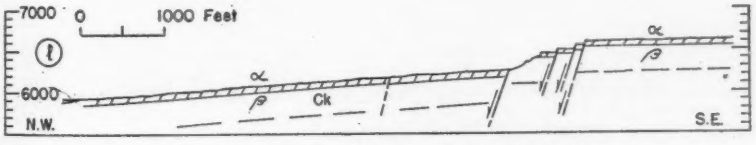

FIGURE 8.—*Structure section across North Road fault*

Circled letter (1) refers to position of section as shown on Plate 1. Ck—Kaibab formation; α—Alpha memberof Kaibab; β—Beta member of Kaibab.

boundary of the Kaibab Forest (Fig. 1; Pls. 1, 3) and continues toward the Arizona-Utah boundary (Fig. 8).

Field observations were carried only a short distance north of the Kaibab Forest boundary, but air photographs and ground views show that the West Kaibab structures continue with little diminution at least to the Arizona-Utah boundary. Between the Kaibab Forest and Arizona-Utah boundaries the structure is that of a somewhat complexly faulted monocline. At the base lies a west-sloping bench of Kaibab and older strata between two normal faults, both downthrown on the west (Fig. 8). The eastern one is a continuation of the North Road fault and has a throw of 200–300 feet. Above this fault is a sloping monoclinal bench terminated on its east side by still another step fault, but of relatively small throw. Above this fault the strata arch upward to the broadly rounded summit of the Kaibab arch, here relatively narrow.

The west Kaibab structure dies out in southern Utah and is replaced by a pronounced regional dip to the northwest. No distinctly localized structure was recognized in the vicinity of Paria, Utah, although the East Kaibab monocline in this locality is at its maximum development with a throw of 4000 feet (Gregory and Moore, 1931).

WESTWARD DIP OF STRATA

Faults and monoclines account for no more than half of the nearly 3000 feet difference in elevation between the Kaibab plateau summit (8500–9300 feet) and the Kanab Plateau to the west (6000–6500 feet). The remaining vertical displacement is accomplished by persistent westward and northwestward dips of 100 to 200 feet per mile. In this respect the western slope of the Kaibab arch differs from the eastern, where virtually the entire displacement is accomplished on one or more strong monoclinal flexures.

DOWNBENDING NEAR FAULTS

A peculiar characteristic of both the Muav Canyon and Big Springs faults, as well as of certain minor faults, is that strata of the downthrown western sides of the faults show a marked dip toward the fault plane as the fault line is approached (Figs. 2, 3, 4; Pl. 1). This is perhaps best illustrated by the Big Springs fault in Nail Canyon (Fig. 4) and is distinctly different from normal drag of beds along the fault. Strata dip 3° to 5° E. within 1000 feet of the fault line. A dip of 9° was measured within 200 feet of the fault at Big Springs Ranger Station; a dip of 11° was measured at a distance of about 800 feet from the fault a mile south of Ryan Ranger Station.

Downbending has been reported by others. Powell (1875, p. 184) noted that

> "in some places in Grand Canyon region the beds at the edge of the table, lying against the foot of the escarpment are turned down, while farther back from the fault, toward the summit edge (of the next fault), the beds are approximately horizontal."

He showed an idealized block diagram of the structure but cited no specific localities. Dutton (1882, p. 185–186) saw

> "in the West Kaibab fault and in parallel step faults into which it divides, that feature which is so frequently observed in many of the great displacements of the district—viz., the turning down of the edges of the thrown beds in the vicinity of the fault plane."

FIGURE 1. RESEQUENT FAULT-LINE SCARP 1 MILE NORTH OF RYAN RANGER STATION
Scarp faces west and is approximately 1000 feet high, exposing Kaibab, Toroweap, Coconino, and Hermit formations. *See* Figure 4, section *g*, for details.

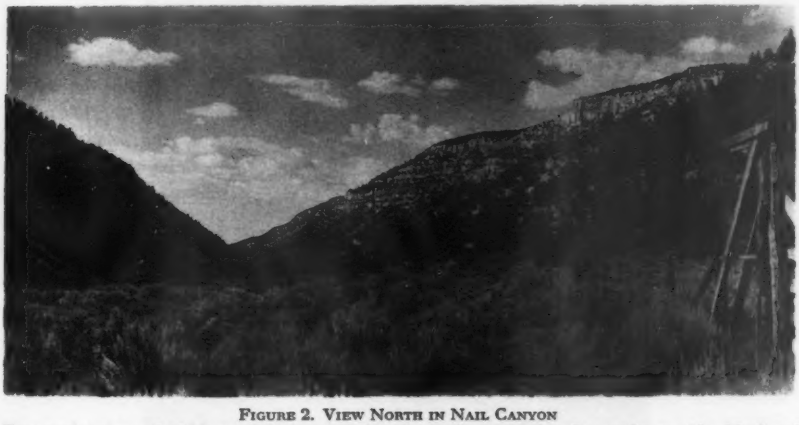

FIGURE 2. VIEW NORTH IN NAIL CANYON
From a point at mouth of Moquitch Canyon. Right side of valley is developed on upthrown side of fault and is about 900 feet high. Left wall of canyon is on downthrow side of fault and is about 300 feet high. *See* Figure 4, section *h*, for details. Nail Canyon is carved by a subsequent stream.

BIG SPRINGS FAULT

FIGURE 1. AIR PHOTOGRAPH SHOWING NORTH ROAD FAULT
Resequent fault-line scarp in Kaibab limestone trenched by small canyons. Conspicuous, sinuous canyon near center occupies minor fault line. For details *see* Plate 1. If relief seems inverted, turn page upside down. Photograph by courtesy of U.S. Department of Agriculture, Forest Service.

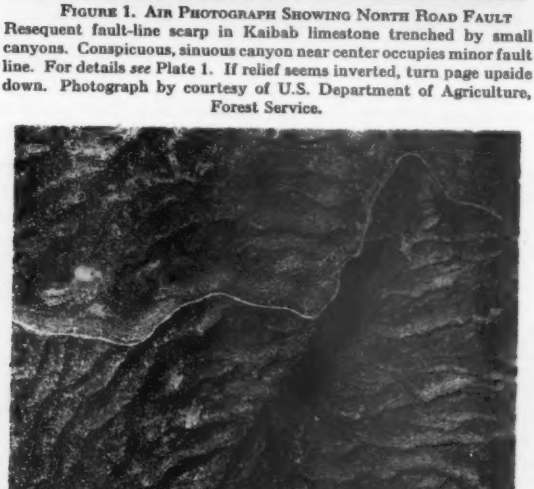

FIGURE 2. AIR PHOTOGRAPH OF TRAIL CANYON FAULT AND EAST KAIBAB MONOCLINE
Fault, downthrown on west side, cuts obliquely across monocline and is occupied by subsequent stream. Other drainage is resequent on stripped Kaibab limestone surface. For details of structure and topography *see* Figure 9 and Plate 1. If relief seems inverted, turn page upside down. Photograph by courtesy of U.S. Department of Agriculture, Forest Service.

NORTH ROAD FAULT AND TRAIL CANYON FAULT

He cited the locality in Nail Canyon and a very conspicuous occurrence in Powell Saddle, where the downbending is visible from as far away as the south rim of Grand Canyon. Both Powell and Dutton made clear that strata were not bent on the upthrown side, an observation borne out in the West Kaibab region by the writer's field observations. In discussing the Hurricane fault to the west, Dutton noted a similar downbending of the beds which, he stated, is matched by a corresponding upbending of strata on the upthrown side. This he interpreted as an earlier monocline of opposite throw which had been broken by the fault. Davis (1901, p. 149–150) employed this relationship as evidence that monoclines of the Grand Canyon district are relatively old structures, along whose lines later faulting occurred in a reverse manner.

Employing the same line of evidence with regard to the West Kaibab faults, Noble (1914, p. 75–76) reported three separate movements along the Muav Canyon fault where it enters the Grand Canyon. The first is of pre-Cambrian age and is not treated in this paper as it affects only older rocks in the lower part of the Grand Canyon. The second displacement recognized by Noble is a monoclinal flexing down to the east, identical to the monoclinal flexing postulated by Dutton and Davis on similar evidence along the Hurricane fault. Downbending of strata as the fault line is approached from the west is Noble's evidence for this distinct period of flexing. The third displacement is the faulting which downdropped strata on the west side to produce the existing West Kaibab faults in the Paleozoic strata. Noble's structure sections show, however, that strata immediately east of the fault lack a corresponding upbending which would be expected of a faulted monocline (Fig. 3). Thus, although his recorded facts in his structure sections accord with Dutton's and the present writer's data, they do not support his own hypothesis of an earlier monoclinal flexure.

More recently, Gardner (1941, p. 254–259) has given considerable attention to the problem of downbending of strata near the Hurricane fault. He observed that downbending of several thousand feet has occurred in Ash Creek Valley, yet strata of the upthrown side of the fault show no corresponding upbending. Gardner argued that the faulting of a previous monocline of opposite throw is unreasonable because, among other things, only an extraordinary type of monocline would result in bending on only one side of a fault which developed along the monoclinal axis. Gardner proposed that faulting occurred through downsagging of strata along the edge of the downthrown block, with little, if any, actual upward movement of the upthrown side. Quite unlike the more conventional concept of entire plateau blocks differentially elevated, Gardner's hypothesis requires only local subsidence along one side of a fault line.

Koons (1945, p. 165–166) restudied the Hurricane fault in the Uinkaret district, south of the area studied by Gardner. Koons found that not only are the beds bent down on the west side of the fault, but beds on the upthrown eastern side of the Hurricane fault are bent up, with dips of 10° to 15°, and can therefore be restored as an earlier monocline broken by faulting in an opposite direction. It seems likely that entirely different structural conditions prevail in the northern and southern parts of the Hurricane fault zone, studied by Gardner and Koons respectively.

Evidence presented by each is convincing, and there is no obvious reason why a sag type of fault movement could not have occurred along certain parts of Plateau faults while in other places faulting occurred along the broken axes of previously formed monoclines. The sag movement is a type of deformation whereas the faulting of an earlier monocline is one step in a set of events in the structural history. The two phenomena are thus not comparable and are not even mutually exclusive.

The structure contour map (Pl. 1) shows that downbending of strata adjacent to faults in the Kaibab region is part of another structural phenomenon—the formation of low anticlines or domes of which the downbent strata are the limbs. Because individual anticlines are limited by the faults, faulting and bending must have been contemporaneous. It is concluded that in the Kaibab region structural evidence of two periods of deformation is absent.

STRUCTURES ON KAIBAB SUMMIT

The summit portion of the Kaibab arch is not a smooth, even arch as generalized descriptions of the Kaibab may have previously implied. It consists, instead, of gentle swells and basins cut by faults ranging in throw from a few feet to 100 feet (Pl. 1).

The highest part of the Kaibab, structurally, consists of an elliptical dome with long axis oriented north-south, lying just west of Demotte Park. This structure is cut on the eastern side by a fault (Pl. 1). Between Pleasant Valley and Jacob Lake are several small faults. Some lie on the flank of the East Kaibab monocline, which they transect obliquely. Two shallow grabens lie just west of the crest of the arch, directly south of Jacob Lake. At Jacob Lake a very clearly defined fault having a throw of about 200 feet runs east-west across the broad plateau summit. A similar east-west fault, of opposite throw, lies northeast of Jacob Lake and is occupied by a canyon down which U. S. Highway 89 runs. This fault abuts a larger fault trending north-northeast across the upper fold of the East Kaibab monocline and deeply trenched by Trail Canyon (Fig. 9; Pl. 3, fig. 2). The Trail Canyon fault, downthrown on the west, is a prominent break in the continuity of the monocline.

Eight miles north of Jacob Lake lies a shallow graben, corresponding to a broad, open depression long known as Summit Valley (Pl. 1). The graben, which trends a little east of north, is bounded on the east side by a single, simple normal fault and on the west side by a series of three or four faults (Fig. 10). Because the floor of summit valley is covered by alluvium the maximum displacement of the graben floor was not determined but is estimated as ranging from 50 to 200 feet.

EAST KAIBAB MONOCLINE

The East Kaibab monocline throughout its extent from Bryce Canyon, Utah, to its southern end in the Cameron-Wupatki region south of Grand Canyon has already been described (Babenroth and Strahler, 1945). The writer has since obtained additional information (Pl. 1) on the structure of the monocline in the Kaibab region as a result of recent field work with the aid of stereoscopic air-photograph coverage, high-quality planimetric base maps, and the Jacob Lake quadrangle

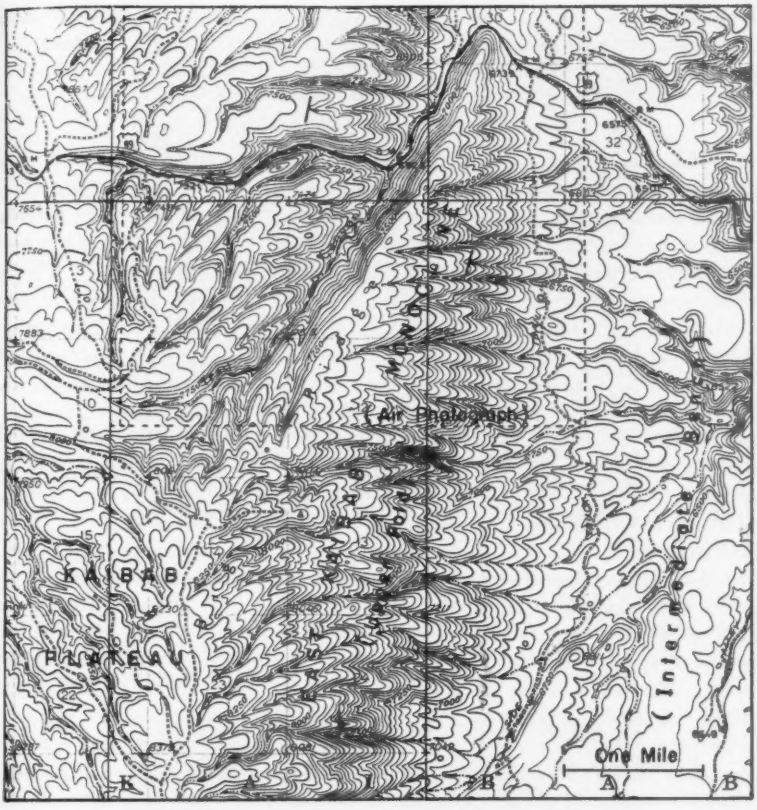

FIGURE 9.—*Portion of Jacob Lake quadrangle topographic map*

Showing East Kaibab monocline and Trail Canyon, along which a fault is located. Dashed line outlines area included in air photograph (Pl. 3, fig. 1). For general structural relations see Plate 1.

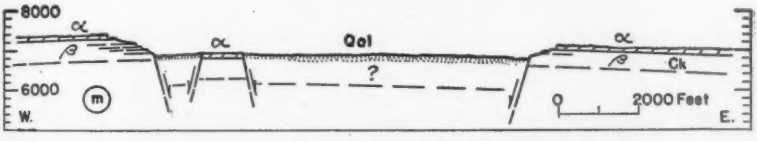

FIGURE 10.—*Structure section across Summit Valley graben*

Circled letter (m) refers to position of section as shown on Plate 1. Ck—Kaibab formation; α—Alpha member of Kaibab; β—Beta member of Kaibab; Qal—recent alluvium.

topographic map of the U. S. Geological Survey (1:62,500); none of these aids was available when the earlier field work was done. The direct and simple manner in which the strata are flexed down more than 3000 feet from the Kaibab summit to the Marble Platform level in the east (Pl. 4) is in marked contrast to the system of regional dips and widely spaced faults by which the strata drop away on the western flank of the Kaibab arch. The asymmetrical character of the Kaibab Plateau,

resembling in some respects a west-tilted fault block with subdued edges, is reflected in the position of a topographic crest close to the eastern edge of the plateau.

STRUCTURAL AND STRATIGRAPHIC EVIDENCE OF AGE OF KAIBAB STRUCTURES

Age of Kaibab structures affecting Paleozoic and Mesozoic rocks cannot be closely determined by structural or stratigraphic evidence. The youngest strata affected by West Kaibab faults and monoclines in Arizona, those of the Triassic Moenkopi formation, are warped conformably with the Kaibab formation in the north end of the Le Fevre graben, within 1 or 2 miles of U. S. Highway 89 (Pl. 1). The East Kaibab monocline likewise affects the Moenkopi in the House Rock area and, northward into Utah, bends all strata up through the Upper Cretaceous. This structure is beveled and unconformably overlain by Eocene Wasatch beds (Babenroth and Strahler, 1945). From this evidence it was concluded that the entire East Kaibab monocline was produced in the Laramian orogeny. If it is assumed, for lack of positive evidence to the contrary, that all Kaibab structures were formed in a single period of deformation, the stratigraphic evidence used to date the East Kaibab monocline in Utah may be extended to cover the entire monocline and it may be tentatively concluded that all the Kaibab structures are of Laramide date.

The absence of lavas and cinder cones in the Kaibab region eliminates criteria which have proved essential in distinguishing relatively recent faults from ancient ones in such neighboring regions as the Uinkaret Plateau (Koons, 1945) and the Cameron-Wupatki region south of Grand Canyon (Babenroth and Strahler, 1945). Absence of Tertiary formations in the Kaibab area eliminates stratigraphic evidence of a type effective in dating the Sevier and Paunsaugunt faults of the High Plateaus in Utah (Gregory, 1944).

Another type of evidence points to relatively great age of Kaibab structures. Monoclinal flexing of Kaibab and older strata in the East Kaibab monocline and in monoclines associated with the more northerly part of the West Kaibab flank would seem to require that a considerable overlying weight of sediments rested upon the Kaibab formation. This idea was first advanced by Walcott (1890) in a discussion of age of the Butte fault and East Kaibab monocline. For similar reasons, Noble (1914, p. 77) concluded that the supposed monoclinal flexing of Paleozoic rocks represented by downbending near the Muav Canyon fault in Powell Saddle "must have occurred not long after erosion began in the region and therefore early in Tertiary time." He added: "The fault that breaks the flexure may have occurred at any time after the greater part of the mass of Mesozoic strata had been eroded away." The writer considers the flexure and fault to be contemporaneous. An early Tertiary date, such as Laramide, is nevertheless compatible with the inference that a considerable thickness of rock overlay the Kaibab formation at the time of flexing.

DESCRIPTIVE GEOMORPHOLOGY

STRIPPED PLATEAU SURFACE

One of the most satisfactory general statements concerning the Kaibab region is that virtually the entire land surface, except for steep canyon walls, is a stripped

FIGURE 1. AIR PHOTOGRAPH OF EAST KAIBAB MONOCLINE AND HOUSE ROCK VALLEY

Canyons of resequent streams incised into east-dipping Kaibab strata of monocline. Crater-like depressions are sinkholes. On right is House Rock Valley underlain by weak Moenkopi and Chinle shales and occupied by north-flowing subsequent stream. *See* Plate 1 for general structural relations. If relief seems inverted, turn page upside down. Photograph by courtesy of U.S. Department of Agriculture, Forest Service.

FIGURE 2. AIR PHOTOGRAPH OF PAGUMP VALLEY AND COCKS COMBS

Subsequent valley, representing a breach of monocline flank, lies between hogback of Kaibab, Toroweap and Coconino beds at base of fold and flat-lying strata of Kaibab Plateau. *See* Plate 1 for structural relations. If relief seems inverted, turn page upside down. Photograph by courtesy of U.S. Department of Agriculture, Forest Service.

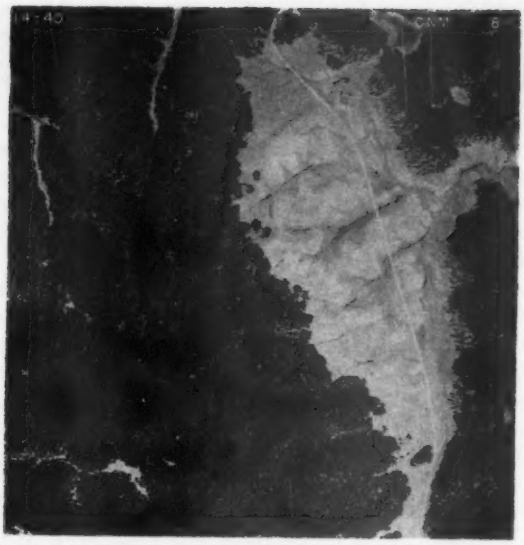

FIGURE 1. AIR PHOTOGRAPH OF PLEASANT VALLEY ON KAIBAB PLATEAU
Light-colored area is open, grassy park floor. Elsewhere forest cover is heavy. Note sinkholes and outcrops of Toroweap limestone in park. Strata in park dip eastward (right) from summit of low dome located at left in photograph. If relief seems inverted, turn page upside down. Photograph by courtesy of U.S. Department of Agriculture, Forest Service.

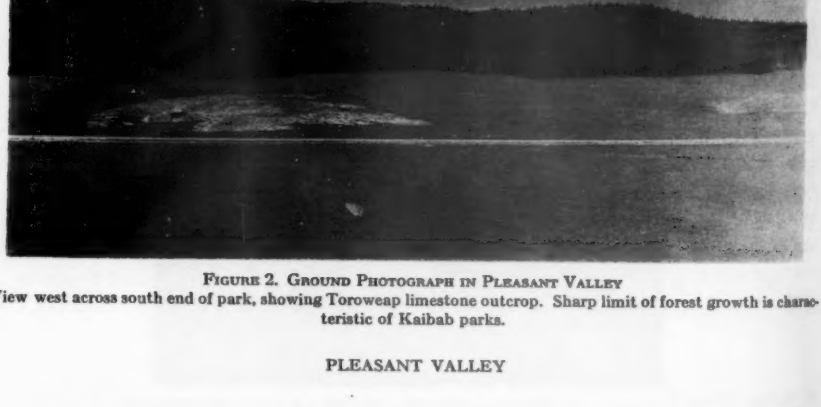

FIGURE 2. GROUND PHOTOGRAPH IN PLEASANT VALLEY
View west across south end of park, showing Toroweap limestone outcrop. Sharp limit of forest growth is characteristic of Kaibab parks.

PLEASANT VALLEY

stratigraphic surface conforming closely to the upper horizon of the Permian Kaibab limestone. Moenkopi and Chinle shales, which formerly overlay the Kaibab to a thickness of 2000 feet or more, have proven so susceptible to erosion by running water that one can imagine that they were removed with much the same ease as a layer of dirt is swept from a concrete walk by the force of water from a garden hose. The process of stripping has been almost completed within the Kaibab region, and the Mesozoic strata have now retreated to the comparatively lower levels of House Rock Valley and the Vermilion Cliffs (Pl. 4, fig. 1). Excellent examples of the process can, however, be seen 7 miles south of Cameron, Arizona, along U. S. Highway 89 where the highway crosses the Black Point monocline (Babenroth and Strahler, 1945).

In the walls of Grand Canyon the remarkable parallelism between plateau surface and stratigraphic horizon is evident to anyone looking to the opposite canyon rim. The U. S. Geological Survey topographic map of Grand Canyon National Park (1:48,000) clearly bears out this observation. Structural benches indicating the position of persistent stratigraphic units keep a fairly constant distance below the rim for many miles. On the Kaibab Plateau, shallow valleys on the sloping west flank exhibit certain conspicuous rock ledges which maintain a uniform position with respect to upland and valley floor for many miles down the regional dip.

Where faults displace the strata, the stripped plateau surface is likewise dislocated. Field observations have shown repeatedly that throw of the faults closely approximates the difference in plateau elevation on either side of the fault line.

The general conformity of surface with structure does not, of course, apply to fine detail of the plateau surface, which is scored by innumerable stream valleys following the dip of the strata (Fig. 11; Pl. 4, fig. 1). These resequent valleys range from a depth of 100 to 200 feet, where dip is gentle on the higher parts of the Kaibab, to steep-walled canyons, 600 to 800 feet deep, cut back into the plateau from the line of the Big Springs fault. Between the valleys are broadly rounded divides, locally widened into flat interstream surfaces. The particular stratigraphic horizon underlying these interstream surfaces varies from place to place. The Kaibab formation consists in its upper part of about 50 feet of thin-bedded magnesian limestones interbedded and underlain by reddish shales, together constituting the Alpha member of the formation (McKee, 1938). Below this lie massive resistant beds of sandy limestones of the Beta member. The magnesian limestone beds of the Alpha are resistant to erosion, but the accompanying red beds have facilitated stripping off of the Alpha beds over large parts of the higher portions of the Kaibab plateau. Although Alpha beds form the surface along the lower part of the East Kaibab monocline and on the lower areas of the West Kaibab slope, they are fortuitously preserved in some elevated and exposed positions high on the plateau.

The Kaibab illustrates the spacing of resequent streams in proportion to dip of strata. Where regional dip of the strata is low, from 100 to 150 feet per mile, valleys are spaced approximately half a mile apart. On monocline slopes where the dip is 10° to 15°, spacing is reduced to one-fifth of a mile (Pl. 4, fig. 1).

Although the vast majority of valleys on the Kaibab and its flanking structures are resequent in origin, a fair number of subsequent streams have excavated along virtually every fault line. Perhaps the most conspicuous subsequent valley is Nail Canyon, which lies on the Big Springs fault line from Dry Park to a point near Ryan

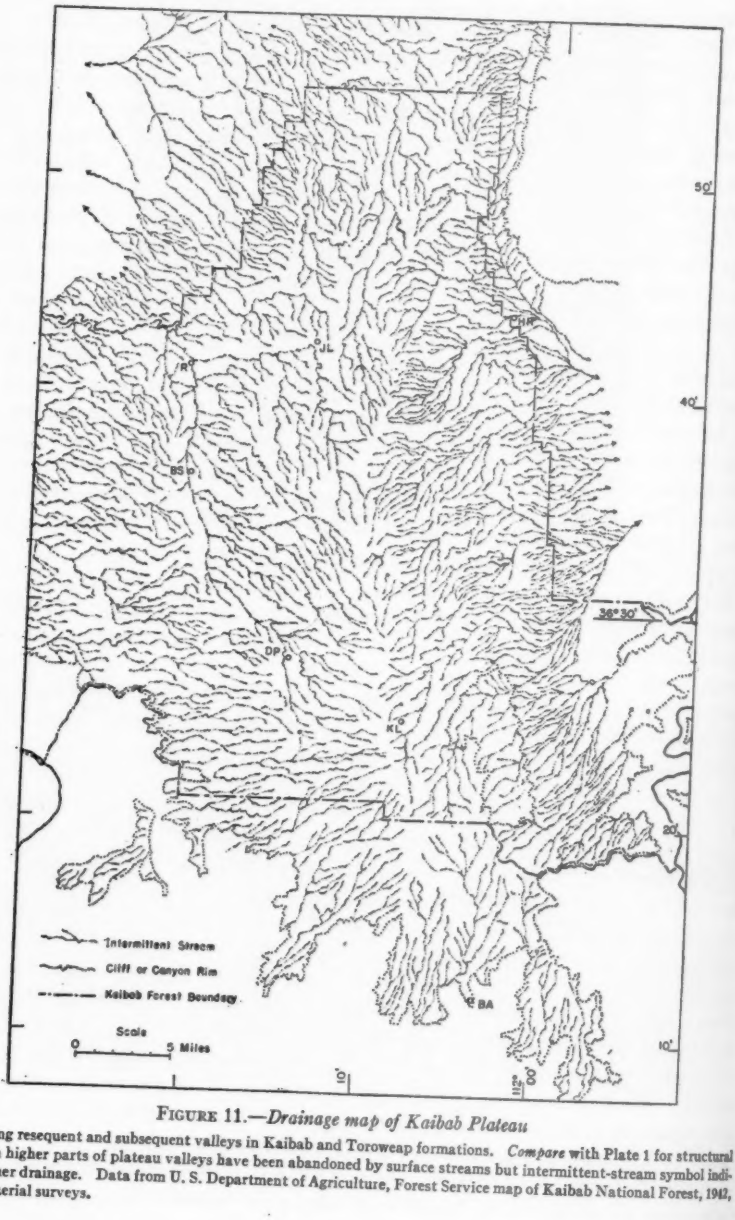

FIGURE 11.—*Drainage map of Kaibab Plateau*

Showing resequent and subsequent valleys in Kaibab and Toroweap formations. *Compare* with Plate 1 for structural data. On higher parts of plateau valleys have been abandoned by surface streams but intermittent-stream symbol indicates former drainage. Data from U. S. Department of Agriculture, Forest Service map of Kaibab National Forest, 1942, based on aerial surveys.

(Pl. 1; Pl. 2, fig. 2). Like other subsequent valleys of the region, Nail Canyon receives many resequent tributaries from the up-dip side of the plateau. Trail Canyon, east of Jacob Lake, is another valley developed by a subsequent stream closely following a conspicuous fault (Fig. 9; Pl. 3, fig. 2).

FAULT-LINE SCARPS

In the absence of Tertiary sediments or lavas anywhere in the immediate vicinity of the West Kaibab faults, evidence as to the recency of faulting depends largely upon geomorphic features. Determination of whether the scarps are fault or fault-line scarps is not as easy as might be supposed upon casual observation. The rapid erosion of weak Moenkopi shales from the resistant Kaibab formation would be expected to produce resequent fault-line scarps of such sharpness and regularity as to make them indistinguishable from true fault scarps produced after the Kaibab surface had been stripped (Pl. 3, fig. 1). In both instances scarps would stand very close to the fault lines and would be abruptly incised by canyons eaten back into the upthrown block, as along the Big Springs fault line. Jacob Canyon, Warm Springs Canyon, Oak Canyon, Moquitch Canyon, and many others issue from the upthrown side of the plateau, but between canyons the general level top of the Kaibab formation is maintained.

The development of subsequent streams along many of the fault lines and the absence of undrained depressions at the scarp bases, reasonable proof that faulting has not been active as recently as the late Pleistocene, are expectable conditions for either a resequent fault-line scarp system or a fault-scarp system subject to moderate erosional development.

In a number of places along the West Kaibab flank resequent streams cross fault lines with little or no deflection (Pl. 3, fig. 1). This is characteristic of most of the Muav Canyon fault north from Big Saddle Camp, of the Big Springs fault north of Ryan, and of the North Road fault. If the faults occurred after resequent streams had been established on a sloping, stripped Kaibab surface, they would have maintained their courses during and after faulting, because they flow from upthrow to downthrow side of the faults. On the other hand, with rapid stripping of weak Moenkopi beds from an ancient fault line, resequent drainage of the existing type would be expected to develop because of favorable westward slope of the stripped Kaibab surface on both sides of the fault. Where downbending is strong, as along Nail Canyon, small resequent streams, following the dip of the downbent strata, flow eastward into Nail Canyon.

Thus no positive statement can be made, but the writer is inclined to favor a resequent fault-line origin because: (1) structural evidence in the form of downbending of the beds as they approach the fault and the general character of anticlinal swells truncated by faults suggest a single period of deformation. Monoclinal flexing, which was a part of this deformation, would seem to require a considerable thickness of younger strata overlying the Kaibab at that time. Hence, present scarps are products of later extensive erosion in this area. (2) In the areas south and east of the Grand Canyon, structurally similar faults and monoclines are present (Babenroth and Strahler, 1945). In some places enough Moenkopi and Shinarump forma-

tions remains to produce obsequent fault-line scarps, in which Triassic beds of the downthrown side of the fault form topographic scarps overlooking stripped Kaibab surfaces on the upthrown side. The closest to the Kaibab region is Gold Butte, near the eastern rim of the Canyon. The obsequent fault-line scarp at Gold Butte, traced south along the fault line, reverses to a resequent scarp where the Triassic beds have been removed. Although evidence of this sort was not found in the West Kaibab area, the similarity of limestone scarps and associated drainage characteristics in the two regions cannot fail to suggest that all belong to the resequent fault-line classification.

PARKS OF THE KAIBAB

Along the summit of the Kaibab arch lie a series of elongate topographic depressions—Demotte Park, Pleasant Valley, Little Pleasant Valley, and Little Park. The largest, Demotte Park, is about 8 miles long and 1 mile wide; the next in size, Pleasant Valley, is about 3 miles long and 1 mile wide (Pl. 5). The depressions trend north and are aligned with only a small mass of plateau upland between them. State Highway 67 runs the length of the entire series of parks, which are thus seen by all travelers visiting the north rim of Grand Canyon. The park floors are grassy, treeless expanses, containing occasional outcrops of limestones and numerous solution sinks (Pl. 5). Walls of the parks rise fairly abruptly along their east sides, rather more gradually on the west sides, and are thickly forested with spruce, fir, aspen, and pine (Pl. 5). The plateau summit zone west of the parks attains elevations of 9100–9200 feet, the highest in the entire Kaibab area, and is generally 300–500 feet above the adjacent park floors. Plateau summit elevations are less on the east side. Moreover, a number of streams drain the parks through rather narrow valleys breaking through the eastern walls of the parks. This eastward surface drainage eventually plunges down steep ravines on the East Kaibab monocline. It is doubtful, however, if a really important part of the park drainage is through these channels. Most of the precipitation in Demotte and Pleasant Valley parks is carried underground by solution passages in the underlying limestones.

A study of the Kaibab parks and other valleys upon the higher parts of the plateau has already been published by the writer (Strahler, 1944c). Evidence was presented that a well-developed system of resequent and subsequent stream valleys on the Kaibab plateau has been disrupted by growth of underground solution passages in the Kaibab and Toroweap limestones. Without active surface streams to remove detritus swept down the valley sides, the valleys became choked with alluvium. Countless alluvial fans from smaller ravines have been built out across the valley floors. Although this hypothesis included the axial parks, the actual development of the depressions and their possible relation to structure was not adequately treated. Recent field work has revealed details of geologic structure in this area (Pl. 1) and permits a more conclusive statement concerning the origin of the Kaibab parks.

Both Demotte Park and Pleasant Valley have been opened out in the eastern flank of a broad anticlinal swell. This swell is broken along its eastern side by a north-south fault which lies beyond the eastern limits of the park walls. Only along the east side of the northern end of Demotte Park and along the east side of Pleasant

Valley is there evidence of faults within the parks, and these are of very small throw. The parks are therefore anticlinal valleys, asymmetrically developed with respect to the anticlinal axis because slightly steeper dips on the east flank of the fold permitted breaching of the strata there first. The east walls of the parks, being obsequent, are somewhat more regular in plan and are steeper than the western slopes of the park in which resequent streams have cut deep valleys (Pl. 5).

Recent field study suggests that the bulk of limestone removal to produce the parks was accomplished by surface streams which opened out an anticlinal valley in the manner common to any region of gentle folds undergoing dissection. The axial subsequent streams, as Davis postulated (1901, p. 155–158), drained eastward through narrow transverse valleys and thence down the East Kaibab monocline. Disruption of drainage through increased limestone solution has been progressing steadily, and eventually even the remaining surface channels may be abandoned. A considerable lowering of the general level of the park floors and resultant broadening and deepening of the park depressions by limestone solution was postulated by the writer (Strahler, 1944c, p. 386) on the basis of limestone exposures in the floor of Pleasant Valley (Pl. 5). These strata were tentatively assigned to the Alpha member of the Kaibab formation, and it was therefore supposed that the limestone masses had in some manner been lowered to the present level of the park floor, perhaps by faulting or by subsidence accompanying solution. More recent field work indicates, however, that these strata are probably the upper beds of the Toroweap formation, which are lithologically similar to the Alpha member of the Kaibab and which would normally be encountered by sufficiently deep erosion.

The fault line paralleling the parks to the east (Pl. 1) has a throw of 50 to 100 feet throughout most of its length and is occupied by a deep subsequent valley in its northern part, northeast of Kaibab Lodge. This valley contains the only surface stream channel of appreciable size seen by the writer on higher parts of the Kaibab plateau. Cutting of this channel into alluvium of the valley floor by an intermittent stream appears to be a recent phenomenon and may have been caused by excavation of gravels for building the highway. All other observation in valleys of the Kaibab strengthen the hypothesis of drainage modification by limestone solution, already fully treated (Strahler, 1944c).

EVIDENCE OF PREVIOUS EROSION CYCLES

The development of a peneplain in the Grand Canyon district at the close of a late Tertiary erosion cycle has been postulated by Davis (1901), Johnson (1909), and Robinson (1907). This peneplain was thought to have been formed at the close of the "Plateau" cycle and to have been greatly dissected and in large part removed in the current, or "Canyon", cycle. These writers supposed that the peneplain was developed to great perfection on areas of Triassic shales which covered the present Marble Platform and Kanab Plateau on either side of the Kaibab uplift. Limestone areas of the Kaibab and Coconino plateaus may have risen distinctly above the surrounding lowlands, but the numerous shallow, open valleys of the Kaibab and Coconino plateaus were cited as evidence of the low relief prevailing at the close of the Plateau cycle.

The writer's field studies in the Kaibab region have shown that, except for the axial chain of parks and the resequent and subsequent valleys, the plateau surface follows closely the upper surface of the Kaibab formation. Field examination of the Kaibab summit has been sufficiently widespread to permit the writer to state with confidence that nowhere are the strata beveled by an erosion surface which could be interpreted as a remnant of a peneplain. On both flanks of the Kaibab arch, in the House Rock locality on the east and the north end of the Le Fevre graben on the west, are small areas of dipping Moenkopi shales perfectly beveled by pediment surfaces. These are of local significance only, and they lie far below the level of the postulated peneplain.

The significance of the shallow, open valleys of the Kaibab and Coconino plateaus in terms of the geomorphic history has been treated at length (Strahler, 1944b). Not only were several lines of evidence presented to show that Davis' cyclic concept for the origin of these features is incompatible with the facts, but a reasonable hypothesis of valley development was proposed in which a single continuous erosion cycle explains all observed landforms of the Kaibab and Coconino plateaus.

Johnson (1909, p. 147–148) stated that the transverse profile of Jacob Canyon, where it debouches from the Big Springs fault-line scarp north of Ryan, consists of a narrow gorge incised into a broad upper valley. The latter he interpreted as a shallow valley formed in the Plateau cycle and intrenched during the ensuing Canyon cycle. Although Johnson recognized that a series of massive limestone beds coincided with the bench in Jacob Canyon, the asymmetric position of the inner gorge with respect to the broad upper portion led him to interpret the profile as one produced by multiple erosion cycles rather than by simple differential weathering and erosion of beds of differing resistance in the canyon wall. The writer's field examinations showed that asymmetry in profile at the mouth of Jacob Canyon is due to a fortuitous bend of the canyon immediately before it emerges from the scarp. The same massive beds may be traced far southward along the scarp and form similar structural benches in every canyon, as well as along the length of the scarp. Along the east wall of Nail Canyon, where the Big Springs scarp is boldest, two groups of massive resistant sandy limestones produce persistent ledges on the scarp face and in all re-entrant canyons. The higher ledge is developed on upper beds of the Beta member, abont 100 feet below the top of the Kaibab formation. The lower ledge, developed on similar massive beds in the Toroweap formation, lies 350–400 feet below the upper ledge and about 175 feet above the top of the Coconino formation (Fig. 4; Pl. 2). Nothing in the character or distribution of these structural benches suggests cyclic significance. They are merely homely equivalents of spectacular benches and terraces seen in the walls of Grand Canyon.

Although no evidence was found in the Kaibab region, the former existence of one or more peneplains at a higher level than the present Kaibab Plateau summit is not excluded. There is a good possibility that the post-Cretaceous–pre-Eocene unconformity exhibited in southern Utah is a buried peneplain which formerly extended southward over the entire Grand Canyon district. Whether this surface was overlain by Eocene strata in the Kaibab area cannot now be determined, but the possi-

bility of superposition of the Colorado River and other major drainage lines from an Eocene cover make the speculation attractive. If the unconformity passed well above the highest part of the Kaibab arch, it would have been destroyed by Tertiary erosion.

Absence of cyclic features in the Kaibab region does not exclude the possible development of erosion surfaces restricted to the weak Moenkopi and Chinle formations when they covered the Marble Platform and Kanab Plateau. Koons (1945) found that remnant erosion surfaces in the Moenkopi shale, preserved under lava cappings of Mts. Logan, Trumbull, and Emma in the Uinkaret region fit together in such a way as to suggest a former pediment sloping from the foot of the retreating high terraces of southern Utah toward the Colorado River at a rate of 250–300 feet per mile. This pediment, developed in late Miocene or early Pliocene time, was fortuitously buried under lavas and is preserved in the three patches mentioned. A similar pediment or extension of the same pediment eastward across the Kanab Platform and a correlative surface in the Marble Platform may have existed, but, because no lavas flowed out upon it, removal was complete in the erosional interval which ensued. The extreme weakness of the shales, in contrast to the resistance of the Kaibab limestones might allow production of such a pediment without development of any distinctive landforms along the Kaibab Plateau flanks. Extensive pedimentation in the belt of weak rocks north of the Colorado would be expected to accompany a general regional denudation. Massive strata of the Paleozoic series in the Grand Canyon rim would serve as local base levels for streams carving the pediments. As Koons has pointed out (1945, p. 178), this landscape development could readily occur in a single cycle of long-continued normal erosion.

Orlo Childs (1948) has found remnants of two extensive pediment systems in the Little Colorado River valley southeast of Grand Canyon. These truncate northeast-dipping Moenkopi, Shinarump, and Chinle formations and were graded with respect to the Little Colorado River. The highest of the pediments, the Black Point surface, is preserved under lavas peripheral to the San Francisco volcanic field. The general development of these surfaces resembles that postulated by Koons for the high-level, south-sloping pediment in the Uinkaret region, but those of the Little Colorado River valley are probably much younger because they lie in the elevation range of 4000 to 5000 feet, whereas pediment remnants of the Uinkaret Plateau are at approximately 7000 feet and are considerably farther downstream in the Colorado River drainage system.

In the Kaibab region small pediment remnants which lie along the base of the East Kaibab monocline near the south end of House Rock Valley (Babenroth and Strahler, 1945, p. 143–144) are at elevations of 5000 to 5500 feet; those which fringe the Vermilion and Echo cliffs (Strahler, 1940), bordering the Marble Platform, range in elevation from 4500 feet in the Lees Ferry re-entrant to about 6000 feet near Cedar Ridge Trading Post. On the basis of elevation, therefore, the formation of these pediments may have been roughly contemporaneous with development of the Little Colorado pediments, although each area possessed its own local base levels on resistant Paleozoic strata underlying the Marble Platform. In both areas today, pedi-

mentation seems to be in progress under inherently favorable conditions of a semiarid climate and a belt of weak sediments bordering a series of retreating plateau escarpments.

ORIGIN OF COLORADO RIVER IN KAIBAB REGION

The concept of the Colorado River in the eastern Grand Canyon as a trench cut across a great barrier, the Kaibab Plateau, with no genetic relation to the structure, was held by Powell (1875, p. 198) and Dutton (1882), who interpreted the river's course as antecedent to the crustal deformation whereby the Kaibab and other dislocations of plateau strata were formed. The concept of discordance between river and structure seems to have persisted among geologists whose visits to the Grand Canyon were casual or who obtained their general knowledge of Grand Canyon development from Dutton's classic report (1882). Nevertheless, Walcott, as early as 1890, recognized that the Colorado River in the eastern end of Grand Canyon is closely related to the East Kaibab monocline and Butte fault. He stated that considerable adjustments in the river's course had come about after the Kaibab arch appeared. Davis (1901, p. 158–167) postulated that the Little Colorado and the part of the Colorado River between Grand Canyon and Lees Ferry developed as a subsequent stream on a weak rock lowland which existed between the Kaibab arch and the Jurassic sandstone cliffs, before they had retreated across the Marble Platform to their present position along the Echo monocline. Davis did not, however, suggest a subsequent origin for the Colorado across the Kaibab-Coconino uplift.

An account of a possible subsequent origin of the Colorado River in the eastern end of the Grand Canyon (Babenroth and Strahler, 1945, p. 137–141) used new structural data as a basis for restoring the topography of the region in such a way as to show that a belt of weak Triassic shales formerly made a subsequent valley encircling the south-plunging end of the Kaibab arch. The ancestral Colorado, it was postulated, occupied this valley but became superposed upon the resistant Paleozoic rocks of the Kaibab arch. Here, then, was revealed a close adaptation of the river to various anticlinal, monoclinal, and fault structures, not previously apparent to students of the region because of inadequacy of maps and structural data. This hypothesis was briefly mentioned by Maxson (1940) who suggested that the river "existed as a powerful stream flowing westerly on a broad flood plain cut on relatively soft Mesozoic sediments during the later Tertiary."

A similar origin is possible for the Colorado River farther west in the Grand Canyon, between Bright Angel Creek and Kanab Creek. The idea was suggested by Noble (1914, p. 90):

> "It seems significant that the northwesterly course of the river is parallel with the strike of the northeastward-dipping flexures of the Coconino fold [Grandview monocline on Pl. 1] and of the West Kaibab fault [downbending on west side of Muav Canyon fault]."

Noble, however, does not state clearly the concept of a broad belt of weak Triassic Moenkopi strata existing as a lowland paralleling the general northwest strike of the western slope of the Kaibab arch in this area.

Figures 12, 13, and 14 illustrate a possible mode of origin of the Colorado River in the Grand Canyon district.

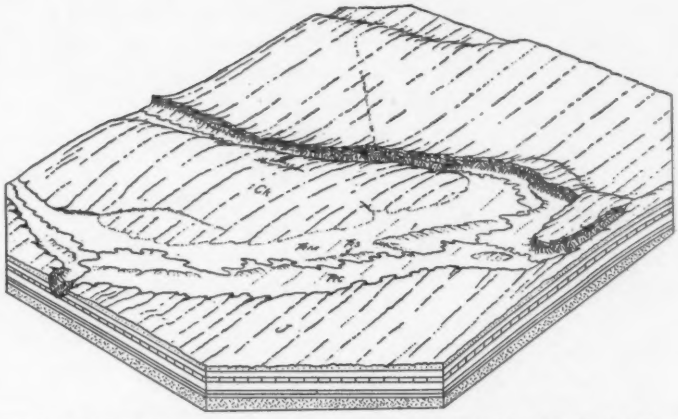

FIGURE 12.—*Block diagiam showing early stage in origin of Colorado River in Kaibab region*

Ancestral river developing as a subsequent stream on a belt of weak Triassic shales encircling south end of Kaibab arch. Ck—Kaibab linestone; T_{rm}—Moenkopi shale; T_{rs}—Shinarump conglomerate; T_{rc}—Lower Chinle shales; J—Jurassic Navajo and Wingate sandstones.

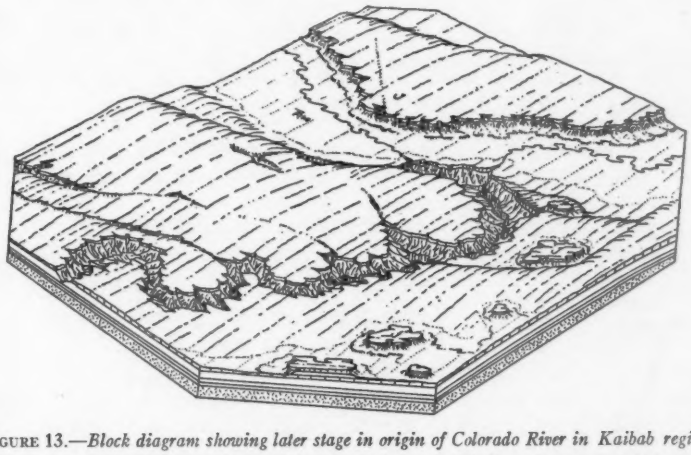

FIGURE 13.—*Block diagram showing later stage in origin of Colorado River in Kaibab region*

River has become incised into resistant Permian Kaibab and older strata while Mesozoic strata are being stripped from adjacent plateaus. *Compare* with Figures 12 and 14.

Figure 12 shows denudation of Jurassic and Triassic strata. Kaibab limestone is exposed over a broad area of the Kaibab arch. The line of Jurassic-Triassic cliffs, formed by the Navajo, Wingate, and upper Chinle sandstones, lies close to the East Kaibab monocline and Butte fault where dips are steep along the East Kaibab monocline, but swings westward around the plunging end of the Kaibab arch, thence trending northwest along the strike of the strong regional dip on the western flank of the arch. The position of this cliff was determined by adding a certain thickness of

strata, based upon thicknesses in the nearest areas where the strata are now preserved, to the surface of the Kaibab limestone shown on the structure contour map (Pl. 1). Between the cliffs and the Kaibab limestone of the arch would have been a broad lowland underlain by Moenkopi and lower Chinle shales and marls, possibly

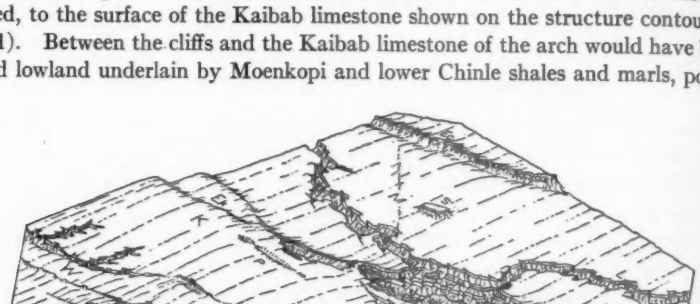

FIGURE 14.—*Block diagram showing Grand Canyon of Colorado River*

Removal of Mesozoic strata virtually complete. River deeply incised across Kaibab-Coconino arch. K—Kaibab Plateau, Ek—East Kaibab monocline; W—West Kaibab faults; P—Kaibab parks; M—Marble Platform; Ec—Echo Cliffs; S—Shinumo Altar; L—Little Colorado River; G—Grandview monocline; C—Coconino Plateau.

divided by a narrow band of the Shinarump formation. An equivalent geologic situation exists today in the little Colorado Valley and along the Vermilion and Echo cliffs.

In the subsequent valley shown in Figure 12, the ancestral Colorado River was developed. Two possibilities exist: (1) The river, a relatively small stream at this time, grew into a major river as a result of downfaulting of the plateau country to the west, along the Grand Wash and Hurricane faults and a possible concomitant elevation of the Plateau country. These events may have allowed incision by the stream into the Paleozoic strata and stimulated it to conquests in its upper part. (2) The Colorado was a major river in early Tertiary time and was superposed across the Kaibab arch from an Eocene cover. As denudation progressed the river shifted downdip along the south-plunging nose of the Kaibab arch until it reached approximately its present position. In either hypothesis, some reason must be shown why the river commenced to cut vertically downward into the Paleozoic strata instead of continuing to shift downdip as the Mezozoic beds were progressively stripped away. Flexures south of the belt of weak rock would have prevented further shifting of the river course (Babenroth and Strahler, 1945, p. 138–139). Similar structures lie along the western side of the Kaibab in the vicinity of south rim of Grand Canyon (Pl. 1). Elevations on the top of the Redwall limestone cliff and the plateau surface near the canyon rim show a low flexure which runs through Fossil Bay and Aztec Amphitheater. This structure may have prevented the river from shifting continuously to

the southwest as denudation progressed. No attempt need be made to fit the broad river bends to minor structural details in this part of the canyon. It is presumed that the river had broad curves within the lowland belt of weak rock and that some local superposition of the river across minor structures might have occurred within this belt. Further discordances or adaptations between the river and minor faults and flexures might be expected during the canyon cutting which followed. Under this hypothesis of river origin, fault lines, such as the Muav Canyon fault, would be less effective in determining the course of the river than broad flexures or regional dips, because faults in the thick, weak Moenkopi and lower Chinle formations have little topographic expression. If, at an earlier stage, the river did occupy the Muav Canyon fault line, it must have abandoned this position in favor of the broad belt of weak rock which would have been situated at a lower elevation a few miles farther southwest.

It would be premature to speculate upon the origin of the Colorado River throughout the entire Plateau province. The hypothesis of subsequent origin outlined above is flexible enough to incorporate into general theories which date the river as early as Eocene, or as late as Pliocene. The local events outlined by the writer could be regarded either as modifications of a previously established course or as steps in the original growth of the river.

DEVELOPMENT OF GRAND CANYON

In the canyon-forming period which followed establishment of the Colorado River in its present location, minor tributaries have widened the canyon and formed a variety of secondary geomorphic features. Various aspects of this problem have been treated by other writers (Dutton, 1882, p. 140–182; Davis, 1901, p. 167–187; McKee, 1929; 1933; Noble, 1914, p. 78–80; Matthes, 1932; Maxson, 1940; 1946). Noble (1914, p. 78–80), in particular, called attention to the control exerted by the Muav Canyon fault and other dislocations associated with the West Kaibab faults upon the development of side canyons, alcoves, and amphitheaters. Asymmetry of the canyon, noticeable in this part of the canyon, as well as in the more easterly parts, was discussed by Babenroth and Strahler (1945).

During canyon development, subsequent and resequent streams of the Kaibab plateau continued to deepen their valleys, but only along the Big Springs fault between Ryan and Big Springs ranger stations and in Pagump Valley, along the East Kaibab monocline, were the Permian limestones breached to reveal the weak Hermit red shales. In these two places, deep, steep-walled valleys have been excavated. Elsewhere the streams have been limited to rather shallow canyons in the limestones. Upon the higher Kaibab, subterranean drainage was increasingly developed, causing abandonment of valleys above about 8000 feet elevation and a reduced rate of cutting of their lower courses (Strahler, 1944c). The rapidly growing Grand Canyon alcoves, favored by vast canyon relief and by access to weak formations under the limestone capping of the plateau, have grown discordantly into the resequent plateau drainage. Numerous diversions of surface drainage are clearly shown on the Grand Canyon topographic map (Fig. 15). Remnants of the plateau surface maintain the resequent drainage lines until entirely consumed, even though the valleys are in some

places truncated both above and below by the canyon rim. Locally, growth of canyon alcoves indicates a dendritic drainage development in which regional dips exert no appreciable control. Elsewhere rectilinear development shows control by fault or joint structures even though no displacement is apparent. Noble (1914, p. 79)

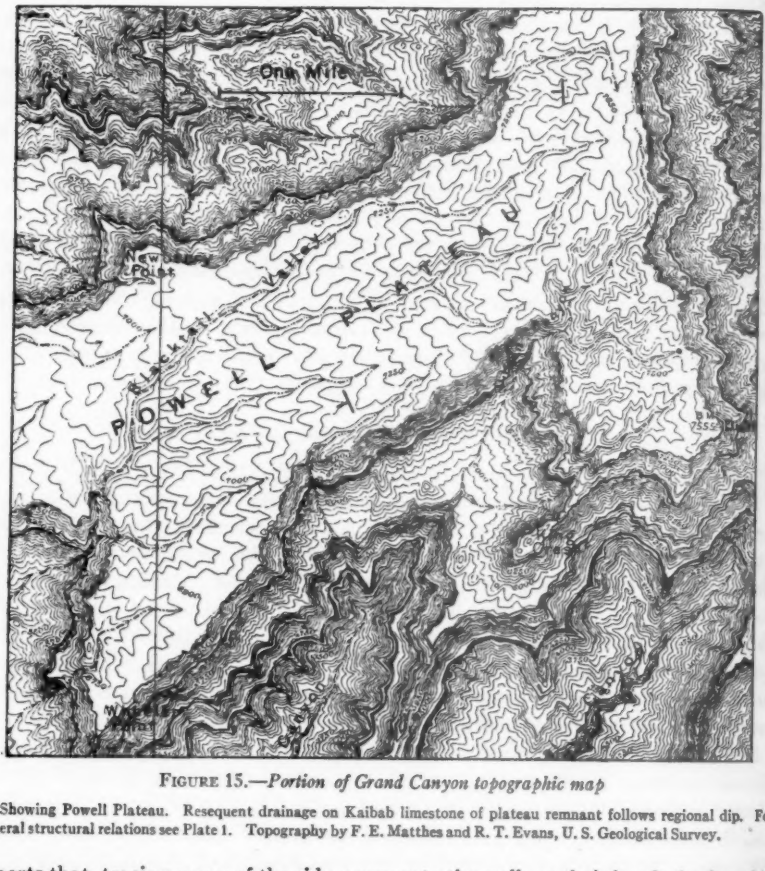

FIGURE 15.—*Portion of Grand Canyon topographic map*

Showing Powell Plateau. Resequent drainage on Kaibab limestone of plateau remnant follows regional dip. For general structural relations see Plate 1. Topography by F. E. Matthes and R. T. Evans, U. S. Geological Survey.

reports that, tracing many of the side canyons to the walls at their heads, he found in the Paleozoic strata lines of shattering that were directly on the main axes of the gorges, although they exhibited no appreciable throw.

SUMMARY

(1) The West Kaibab zone consists of three principal normal faults, downthrown on the west, and locally giving way in part to equivalent monoclinal flexing. Persistant westward regional dips between the Kaibab crest and the Kanab platform account for at least half the total displacement of 2500 to 3000 feet. Various minor faults and flexures were also mapped.

(2) Downbending of strata on downthrown sides of faults as the fault line is approached is characteristic of West Kaibab faults and is interpreted as downward sag of strata near the fault rather than as an earlier monocline of opposite throw.

(3) The summit portion of the Kaibab arch is warped into low domelike swells and basins, cut by minor normal faults. North of Jacob Lake a broad, shallow graben trending north occupies the summit of the Kaibab arch.

(4) No evidence was found for more than one period of deformation in the Kaibab region. Existence of monoclines on both flanks of the fold suggests deformation under a considerable thickness of overlying strata. A Laramide date for a single period of deformation has tentatively been applied to all Kaibab structures.

(5) Virtually the entire drainage system of the Kaibab arch consists of resequent streams, following the regional dip of the strata with remarkable persistence, and a few subsequent streams located on fault lines. This drainage system came into existence as Mesozoic strata were stripped from the resistant Kaibab limestone formation.

(6) All scarps along fault lines of the Kaibab region are tentatively classified as resequent fault-line scarps in the absence of proof of any late Tertiary faulting. Sharp delineation and little erosion of limestone fault-line scarps are explained by the rapidity with which weak overlying Moenkopi and Chinle formations are swept away by fluvial processes.

(7) Parks of the Kaibab have resulted from breaching of the eastern flank of a gentle anticline. Surface drainage, passing through gaps in the east wall of the park chain, is being reduced by extensive development of sinkholes on the park floors.

(8) No evidence was found in the Kaibab region of a peneplain produced in the hypothetical Plateau cycle postulated by Davis, Johnson, and Robinson. Such geomorphic features as open Kaibab valleys and composite valley profiles are explained as normal forms of a single continuous cycle of denudation. No beveling of strata was found on the Kaibab Plateau. If the Plateau cycle peneplain was developed only on weak Mesozoic shales on either side of the Kaibab arch, evidence has disappeared along with the weak rocks.

(9) Pediment remnants along the base of the East Kaibab monocline near House Rock and near the mouth of Le Fevre graben near the base of the West Kaibab fault zone may have been formed contemporaneously with pediments of the Little Colorado valley, but have no significance as indicators of important regional cycles of erosion.

(10) The Colorado River in the Kaibab region may have established its present course as a subsequent stream in a lowland of weak Moenkopi and lower Chinle shales which at one time in the regional denudation encircled the southern end of the plunging Kaibab arch. Further study must determine whether the river originated by some other process in early Tertiary time and adjusted its course to this weak rock belt, or whether it grew in later Tertiary time by following the favorable structure.

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PLEISTOCENE OF THE GREAT PLAINS

INTRODUCTION

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The Pleistocene period is a geologic time unit of great interest to students of the earth sciences, not only because of the unusual sequence of glacial advances and retreats that took place during its extent, but also because it is the most recent of the defined geologic periods, the period closest to us in time, the period in which our own immediate ancestors had their origin and went through much of their development. Consequently, the Pleistocene period has received a much greater degree of attention than has any other single period in geologic history. Many specialists have worked on the various aspects of Pleistocene history, and many avenues of approach have been followed in the efforts to come to some understanding about this latest, and in many ways most interesting, of the geologic periods.

Yet in spite of the great amount of work that has been devoted to the study of Pleistocene history, there is much that still remains to be done. Many problems are unsolved, while for many more problems only partial solutions have been reached. The reason for this state of affairs is in part owing to the peculiar difficulties inherent in the problems of Pleistocene history. We are so close to this geologic period that we lack the perspective of geologic time that is present in our view of the earlier periods of earth history. Being so close to the Pleistocene period in time we frequently see masses of details that are confusing rather than helpful to us. The definition of boundaries are blurred and fuzzy—not sharply defined as they so frequently are in the earlier periods. We are in effect living in the end phases of Pleistocene history; we are in the midst of Pleistocene events that are still taking place. In some ways this is helpful to us, in other ways it is not.

Among the many problems of Pleistocene history are those of the defining boundaries for the beginning and for the end of the period. Both of these boundaries are difficult to establish. There is the question, which is of course in part academic, as to whether we are actually out of the Pleistocene period as yet. Perhaps we are not; perhaps we are still living in an interglacial interval that at some future date will be followed by another period of refrigeration and glacial advance. And in spite of the fact that we are at some distance, geologically speaking, from the beginning of the Pleistocene period, we find the greatest of difficulty in defining even this boundary. Consequently opinions as to what constitutes the Pleistocene, and where the division between this period and the preceding Pliocene period is to be drawn is ever the subject of much debate.

With these considerations in mind, a symposium on the Pleistocene of the Great Plains was held at the Fifty-ninth Annual Meeting of the Geological Society of

America. The purpose of this symposium was to discuss the problem of Pleistocene history in central North America, particularly with reference to the criteria for dating the beginning of the period. And although the symposium was entitled "Pleistocene of the Great Plains", it might very appropriately have been called "The Beginning of the Pleistocene in the Great Plains", for all participants in the symposium quite evidently were concerned, above everything else, with the problem of the proper division between the Pliocene and the Pleistocene; with the criteria that should be used for defining the beginning of Pleistocene history in central North America.

The symposium was divided into three parts. The first section was entitled "Beginning of the Pleistocene in Eastern United States," and the subject was presented by Richard Foster Flint. This topic was discussed by Arthur Bevan, Maxim K. Elias, and Richard Foster Flint.

The second part of the symposium was headed "The Age of the Blancan Faunas", and the opening presentation was made by Paul O. McGrew. Following this, papers were presented by Claude Hibbard, by C. Bertrand Schultz and Thompson M. Stout, and by A. D. Leonard. Participating in the discussion were Claude Hibbard, Richard Foster Flint, Paul O. McGrew, R. A. Stirton, Thompson M. Stout, and Horace Elmer Wood.

The third part of the symposium, which might be considered as mainly a continuation of the second part, had to do with "The Pliocene-Pleistocene Boundary in the Great Plains". Obviously, a consideration of this problem integrates so closely with the problem of the Blancan faunas that no real division between the two topics can be made. The opening paper was presented by John C. Frye, followed by presentations by Wallace W. Atwood and Wallace W. Atwood, Jr., by Maxim K. Elias, by E. C. Reed, and by Glenn L. Evans. Discussions were presented by John C. Frye, Claude Hibbard, A. L. Lugn, E. C. Reed, C. Bertrand Schultz, and M. Y. Williams.

In the following pages of this Bulletin the formal papers presented by the several participants in the symposium are now published. These papers are arranged in the order in which they were presented, being grouped into three sections according to the manner in which the symposium was divided into three general topics for consideration. Following the formal papers the discussions, as revised by discussants, are published. These too have been grouped under the three headings to which they are pertinent.

Whether a symposium such as this can lead to immediately visible results is a question. Opinions will still be held, and in many cases these opinions will differ. But the symposium did allow for a meeting of minds on a subject of great importance to the profession of geology, and for this reason much good will come out of it. An important problem has been discussed and argued; the results are now printed for careful consideration by geologists the world over.

BEGINNING OF THE PLEISTOCENE IN EASTERN UNITED STATES

INTRODUCTION

BY RICHARD FOSTER FLINT

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A thorough discussion of the beginning of the Pleistocene in any region must involve an attempt to define the Pleistocene series and to fix the position of its base. For this purpose a continuous Pliocene-Pleistocene succession must be looked for. At least two marine sequences of this kind are well known. One is the so-called crag sequence on the east coast of England, marine deposits whose faunas record warm-temperate water gradually becoming colder, with actual arctic mollusks at the top. The other is the marine succession in southwestern California, in which cold-water faunal zones occur in an otherwise warmer-water sequence. In strata such as those of eastern England and southwestern California it should be possible to agree upon the Pliocene-Pleistocene boundary, on a basis of climatic change implied by water temperatures.

Among terrestrial deposits likewise, there are transitional sequences. Examples are the Villafranchian sequence in the Arno Valley in Italy, and the San Pedro Valley sequence in Cochise County, Arizona. The transitional character of both examples rests on their vertebrate faunas, which include both Pliocene and Pleistocene genera. Here, too, it should be possible eventually to agree upon the critical stratigraphic boundary after the relations of the critical genera elsewhere have become better known.

EASTERN UNITED STATES

In eastern United States the Pliocene-Pleistocene stratigraphic sequence is more complicated, in that it involves considerable breaks. However, it has not been thoroughly studied, and there is basis for the hope that suitably directed study would produce results significant for fixing the base of the Pleistocene.

In places along the coast from the Carolinas to Florida occur marine deposits of undoubted Pliocene date, with faunas that imply relatively warm water temperatures. These deposits include the Croatan, Waccamaw, Charlton, and Caloosahatchie formations. Farther inland on the Coastal Plain, not only in the South Atlantic States but occurring discontinuously from the Cape Cod district to the lower Mississippi River, are extensive areas of highly quartzose gravel and sand (and along the Gulf Coast, silt and clay). These sediments, on the Atlantic Coast at least, indicate selective weathering and deposition by streams. They have never been studied as a whole, but throughout long distances they appear to have the same general character. They are known under various regional or local names, such as Citronelle formation, Bryn Mawr gravel, Beacon Hill gravel, Mannetto gravel, and Aquinnah conglomerate. In eastern Pennsylvania, gravels of this type lie upon eroded surfaces that have been referred to the Harrisburg (Pliocene?) erosion cycle. These sediments have been rather generally regarded as alluvial, and on good grounds.

Apparently they were deposited by streams flowing radially off the Appalachian dome during and immediately following a conspicuous upbowing of that structure. In the northeast these sediments, unlike some later deposits, include no material that demands the presence of glaciers. On the South Atlantic and Gulf coastal plain, these sediments are unconformably overlain by Pleistocene marine so-called "terrace" sediments. Partly for these reasons in the northeast, and partly because of a contained fossil flora on the Gulf Coast, these alluvial deposits have been regarded by many as Pliocene, although Fuller thought the Mannetto gravel on Long Island was Pleistocene, the Aquinnah conglomerate contains a horse referred to the Pleistocene, and it has been suggested that the Citronelle is Pleistocene. Thus the dating of these widespread alluvial sediments is by no means firmly established.

Further, unfortunately, no physical connection has been firmly established between these terrestrial deposits and the marine Pliocene of the Coastal Plain. MacNeil has made the suggestion that alluvial sandy sediments (apparently Citronelle) in southeastern Georgia may pass seaward into the marine Charlton formation, which is Pliocene. On the other hand a stratum encountered in drilling at Mobile, Alabama, contains a fossil pelecypod (a *Rangia*) that suggests correlation with the Charlton formation, although on a basis of its vertical position this stratum would seem to be pre-Citronelle (F. Stearns MacNeil, unpublished communication). More detailed studies than have been made hitherto would go far toward establishing correlation between marine and terrestrial Pliocene deposits in the Atlantic-Gulf coastal region, and toward fixing the Pliocene-Pleistocene boundary.

In eastern United States, Pleistocene sediments are widespread, but nowhere are they known to be transitional from the Pliocene. In the glaciated region of New Jersey-New York-New England, glacial drifts are present, but it is not certain that any of them is older than Kansan. Therefore the lowest Pleistocene is not certainly represented.

In New Jersey, south of the limit of glaciation, the oldest recognized Pleistocene deposit is the Bridgeton formation. This is coarse, gravelly alluvium built by the Delaware and other rivers probably during the Aftonian and Kansan ages. As correlatives of the Nebraskan drift are not known in that region, there too we have to deal with a basal Pleistocene hiatus. In eastern Pennsylvania and Maryland the alluvial Brandywine and similar gravels occur, chiefly as thin covers on strath terraces along major streams, and represent conditions generally similar to those of the Bridgeton in New Jersey.

From the James River in Virginia southward through the Coastal Plain there are extensive though very thin Pleistocene sediments, both marine and alluvial. These are the so-called "terraces," and opinions about them differ. The simplest interpretation of these sediments is, I believe, the one I have tentatively put forward elsewhere. It is far from proved that the actual situation is as simple, but, until it is proved otherwise, the simplest explanation seems to me to afford the safest working hypothesis. This is that there are three principal Pleistocene strand lines and related marine sedimentary veneers, corresponding to three interglacial sea levels higher than the present sea level—namely, Aftonian, Yarmouth, and Sangamon. I suggest that the highest marine deposits in western Florida and apparently overlying the

Citronelle formation in southern Georgia[1] are Aftonian, and that these were gently warped prior to Yarmouth time. I suggest further that the Surry strandline at about 100 feet, and the Suffolk strand line at about 25 feet, neither of which is deformed, together with related sea-floor deposits, represent the Yarmouth and Sangamon interglacials respectively.

The Pamlico formation—the marine veneer related to the Suffolk strand line—carries a warm-water invertebrate fauna. Otherwise the sediments of this group have not yet yielded significant fossils. Hence the suggested dating rests on physical rather than faunal evidence. Here again we lack deposits of recognized Nebraskan age. Such deposits presumably were laid down on the sea floor when the surface of the sea was considerably lower than it is today, though in Florida perhaps this floor has since been warped up. At any rate, here as elsewhere there seems to be a basal Pleistocene hiatus.

CENTRAL UNITED STATES

The Nebraskan drift, the oldest known drift in the Illinois-Missouri-Iowa region, overlies beveled Paleozoic rocks. It is apparently younger than the buried Teays valley system (Horberg, 1946). In many localities the oldest till present (not necessarily the Nebraskan) contains incorporated quartzose gravel (Shaw, 1912, p. 8; Lamar and Sutton, 1930, p. 857; Wanless, 1929, p. 91) similar to gravel occurring outside the glaciated region, and thought to be Pliocene. Although shown to be preglacial (Chamberlin and Salisbury, 1891, p. 372) this gravel has never been proved to be Pliocene. It appears (though it has not been conclusively shown) to grade down the Mississippi Valley into the Citronelle formation (Spooner, 1935, p. 109; Stephenson, Logan, and Waring, 1928, p. 61).

There is no sedimentary evidence of the events that occurred between the deposition of this quartzose gravel and the arrival of the Nebraskan glacier. We have no choice but to take the base of the Nebraskan drift as the base of the Pleistocene.

Although central United States lacks a suitable marine sequence, it supplies better evidence than the Atlantic Coast in this respect—that the oldest drift in the Central Region is indubitably Nebraskan—, whereas in the east no drift has been certainly recognized as older than Kansan.

THE PLIOCENE-PLEISTOCENE BOUNDARY

In summary, no continuous sedimentary sequence, either marine or terrestrial, such as those in southwestern California, Arizona, England or Italy, occurs in eastern or central United States. In the latter region Pleistocene deposits have been identified chiefly on a basis of their *relation to glaciation*—a relation that is direct in the case of drift deposits and indirect in the case of undeformed high-level marine deposits with their implication of high interglacial sea levels. Thus we find, typically, glacial or interglacial sediments directly overlying sediments of nonglacial character. Most geologists would place the Pliocene-Pleistocene boundary, with little hesitation, at the base of the lowest glacial or interglacial sediments. On this basis the

[1] This relationship suggested by F. Stearns MacNeil (unpublished communication).

boundary in eastern and central United States can be said to be fairly well defined.

This same boundary, however, as identified at present in other parts of the world is not marked by a readily recognizable break. Many published references tell us of transitional sequences without significant break.

Because of the lack of a conspicuous physical break Lyell made his famous separation of Pleistocene from Pliocene in the Paris basin on a basis of percentage of mollusk species still living. Since Lyell's time his percentage has had to be altered, but as it varies from region to region it does not seem to be widely useful.

Despite these difficulties, it is essential that the Pleistocene be recognized as a separate unit. Hence we must find a sound general basis for distinguishing it from the Pliocene.

CLIMATE AS THE BASIS OF DISTINCTION BETWEEN PLIOCENE AND PLEISTOCENE

In the absence of the means of differentiation commonly used in older strata, I believe the best general basis of separating Pleistocene from Pliocene is climate. The climates that resulted in extensive glaciation constitute the one outstanding and basic respect in which Pleistocene time differed from the time preceding it. Were it not for these climatic differences, Pliocene and Pleistocene would probably never have been differentiated.

According to the present weight of evidence the great climatic fluctuations were simultaneous throughout the world, and their direct and indirect effects were profound. The major direct result was the burial (at the glacial maximum) of about 32 per cent of the land area of the world beneath glacier ice, and the imprinting on most of this area of a conspicuous identifiable record. Another result, extending for hundreds of miles into the nonglaciated land areas, was outwash sedimentation, making possible the correlation of features in additional wide nonglaciated regions. A third result was the conspicuous change wrought by moist (pluvial) climates in the now desert and semidesert regions of middle and low latitudes, creating lakes and streams and altogether affecting another 10 per cent of the world's land area. A fourth result was the notable fluctuation of sea level that took place in sympathy with the fluctuating glaciers. It affected all the coasts of the world and temporarily added (at the greatest glacial maximum) 2 or 3 per cent to the land area of the world by exposing extensive areas of continental shelf. Finally, a fifth result consisted of widespread migrations of animals and plants, leaving at any one place a record of different assemblages at different times, not only on the nonglaciated lands but in the floor deposits of shallow seas as well.

The existence and wide extent of all these related features make a strong case for the use of climate as a basis for the definition (and also for the subdivision) of the Pleistocene, which should be thought of as beginning with the first evidence, direct or indirect, of the existence of a notably cool climate. On the other hand marine and terrestrial sediments in very low latitudes where the influence of climatic change was comparatively slight may demand some additional and more local basis for correlation, although it seems probable that as knowledge increases even these can be related in one way or another to contemporaneous events in higher latitudes.

It is true that the beginning of glaciation was not everywhere contemporaneous. Glaciers formed in high mountains long before they invaded lowlands in middle latitudes. But this fact does not constitute a valid objection to the use of climatic fluctuation as a basis of correlation. Similar lack of time equivalence is a characteristic of the majority of stratigraphic basal horizons. The encroachment and regression of any Paleozoic sea was a gradual and progressive event. The time unit represented by its deposits began much earlier in some places than in others. Yet the unconformity at the base of the deposits is accepted as marking the beginning of the new stratigraphic unit. The unconformity at the base of the earliest glacial deposits should be treated in the same way.

A different basis of distinction that may have much value in some regions and that may be (though not necessarily so) independent of climatic fluctuation must be considered also. Haug suggested that the Pleistocene might be regarded as beginning with the appearance of *Bos*, *Elephas* (in the broad sense), and *Equus*. This suggestion has been approved by several paleontologists and has been extended to include the modern camel types and man (Haug, 1907–1911, p. 1776; Hopwood, 1935, p. 47; Colbert, 1942a; 1942b). If, as is quite possible, these forms should prove, through their relationship to the climatic evidence, to be peculiar to the Pleistocene and therefore true Pleistocene guide fossils, this fact would have great practical usefulness. The wide provisional adoption of this group of fossil forms as Pleistocene constitutes a logical argument in favor of incorporating the concept into any working definition of the Pleistocene.

CONCLUSION

The present conference is a fine example of co-ordination of effort in various related fields of research, and I count it a privilege to take part in it. I should like to be thought of, not as a glacial geologist, but as one ready to take the broadest view of the Pleistocene; as one ready to confer with any vertebrate paleontologist, any invertebrate paleontologist, or any stratigrapher, to reach a workable compromise definition of the Pleistocene. Such a definition must be one we can all agree upon, whether we are concentrating in the marine Pleistocene of California, the alluvial and eolian Pleistocene of the Plains, or the glacial Pleistocene of northern North America.

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THE BLANCAN FAUNAS, THEIR AGE AND CORRELATION

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INTRODUCTION

The Blancan faunas of North America represent the last group of Pliocene faunas, the first group of Pleistocene faunas, or they are transitional and overlap both. Because of this critical position it is a very desirable function of this conference to consider the available data to see if we are justified at present in assigning the time unit definitely to one epoch or the other and thereby determining exactly what represents the Pliocene-Pleistocene boundary west of the glaciated regions.

To begin with we need a clear definition of the term Blancan—and the term might not be easy to define to the satisfaction of all concerned. The original definition is strictly faunal. It was based by the G. S. A. Committee headed by Horace Wood 2nd on the local fauna at Mt. Blanco in Texas. The principle correlatives were listed as the Rexroad of Kansas, the Benson of Arizona, and the Hagerman of Idaho. The index fossils, first appearances, last appearances, and characteristic fossils were named. This has proved a very workable definition for the paleontologist, but it does not enable the stratigrapher to define more than local deposits and then only if fossils are present.

The faunal definition is clear cut, and because the Blancan time unit was almost certainly of very short duration the correlations are probably much more definitive than most.

The Blancan was immediately preceded by an important wave of extinction that wiped out at least 25 genera that left no descendants. Among these are such common Pliocene forms as rhinoceroses, neohipparions and other horses, many antilocaprids, and various carnivores and rodents. The absence of these genera serve to distinguish clearly the Blancan from the preceding Hemphillian faunas.

Of the many genera that survived into the Blancan only three or four failed to live through the Pleistocene, and these few died out at the end of the Blancan.

There are at least three genera that are diagnostic for the Blancan: *Plesippus* (or as I prefer *Hippotigris*), *Borophagus*, and *Procastoroides*. All of these were derived from autochthonous stocks. *Mimomys*, an Old World immigrant, may also be an index.

The largest group of mammals found in Blancan faunas are the new genera that appear first at this time and which live on through the Pleistocene. About half of these are immigrants from South America and Asia, and the other half are new genera derived from autochthonous ancestors.

A last group of genera includes those that appear first after the close of Blancan time and are characteristic of all post-Blancan faunas. These are all large animals and are all (with the possible exception of *Equus*) Old World immigrants.

DO THE BLANCAN MAMMALS OFFER EVIDENCE THAT WILL HELP IN DETERMINING THE PLIOCENE-PLEISTOCENE BOUNDARY?

The evidence bearing on this question can be divided into several subheads.

GENERAL FAUNAL RELATIONSHIPS: Figure 1 shows clearly that the major faunal break is between the Hemphillian and the Blancan. If we were to draw the line

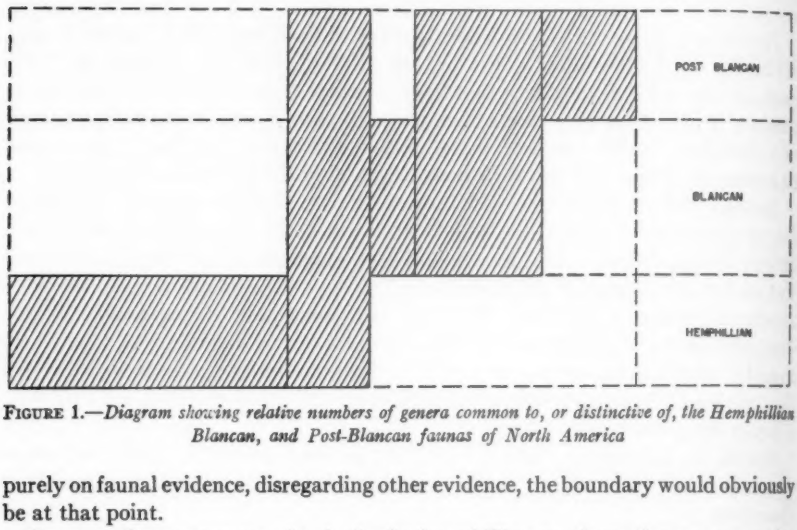

FIGURE 1.—*Diagram showing relative numbers of genera common to, or distinctive of, the Hemphillian Blancan, and Post-Blancan faunas of North America*

purely on faunal evidence, disregarding other evidence, the boundary would obviously be at that point.

GENERAL DIASTROPHISM: At the beginning of Blancan times there was a major influx of immigrants from both Asia and South America. Old World immigrants include *Onochomys*, *Synaptomys*, *Ondatra*, *Sigmodon*, *Neotoma*, *Castor*, *Mimomys*, *Odocoileus*, and *Stegomastodon*—with one exception rather small mammals. In very strong contrast is the wave that followed the Blancan when such mammals as *Archidiskodon*, *Mammonteous*, *Parelephas*, *Bison*, *Symbos*, *Cervalces*, and, I believe, *Equus* —all large forms—made their appearance. To me this suggests but one major emergence of the Bering land connection. These animals did not reach the plains of North America by migration but rather by expansion. The range was expanded by generations and not appreciably by individuals. Because elephants breed much more slowly than rodents I believe that if the path to North America were suddenly opened and proboscidians, large artiodactyls, and rodents were in a position to use this path the rodents would reach the Plains long before the elephants and artiodactyls. My conclusion is that the land connection that opened North America to the large mammals that reached the Plains after the close of the Blancan was the same one that opened the way for the rodents. The short duration of Blancan time must be considered in this connection. Because fossil-bearing rocks of Blancan age are not known in the far North I know of no way to prove this point at present. At any rate there is definite faunal evidence suggesting important emergence of the area between North America and Asia during the break between Hemphillian and Blancan times.

The Blancan faunas offer clear evidence that the Panamanian isthmus was opened for the first time since early Tertiary at the beginning of the Blancan. Porcupines, capybaras, glyptodonts, and two genera of large ground sloths, a combination that almost had to have hard ground to cross on, made their first appearance at this time.

For these reasons the faunas of the Blancan suggest that the break between Hemphillian and Blancan was coincident with important and wide-spread land elevation.

CLIMATIC CHANGE: There is abundant evidence that during the Blancan there was at least one period of cold and moist climate. The Grandview and Hagerman faunas, both typically Blancan, contain rodents that live now under very moist conditions and lemmings that are restricted to boreal climates. This led J. R. Schultz to the conclusion that glacial conditions may have been well advanced during the deposition of these beds.

The fauna of the Meade gravels has been thoroughly studied by Hibbard, and he has shown that they contain boreal elements. In support of this he has found striated boulders that he interpreted as having been marked by glaciers in the Rocky Mountains and transported to the Meade area in floating ice. This fauna is small but contains both *Plesippus* and *Nannippus*—good Blancan genera. The conclusion drawn from these facts is that cold and moist climate, perhaps a glacial climate, prevailed during the later part of the Blancan.

HAVE BLANCAN MAMMALS BEEN FOUND IN ROCKS OF THE GLACIATED REGION?

There are two records of *Nannippus* being found in deposits of undoubted Pleistocene age in Iowa and Missouri. It has nearly always been assumed that these fossils were redeposited from older sediments. It is a possibility that certainly must be considered, but I know of no possible source from which they could have been reworked. Any definite conclusion concerning these Blancan forms should await more evidence.

CAN THE BLANCAN BE PRE-GLACIAL AND STILL BE PLEISTOCENE?

Hibbard has made detailed studies of the Rexroad, a Blancan fauna from Kansas. There are many rodents in the fauna but none that indicate a cool climate. Therefore, and with good reason, Hibbard regards the Rexroad as pre-Nebraskan and therefore Pliocene.

In my opinion the fact that the Rexroad and other "warm" Blancan faunas are pre-Nebraskan does not necessarily mean that they are pre-Pleistocene. This, of course, depends upon one's definition of the term Pleistocene.

It is obvious that ice started to accumulate in the far north long before there was any direct evidence of ice in the plains. Similarly, I believe, the effects of cold climate would be reflected first in the far north and as the ice spread slowly southward it would be only slightly preceded by real evidence of cold climate. Some Blancan faunas reflect definite evidence of moist and cold conditions, and some apparently do not. I have been unable to find any detectable evidence of evolution in the mammals of the Blancan, so the exact succession of these faunas cannot be determined in the usual way. This is indicative of the short time represented by the unit. If we consider the beginning of Pleistocene as being that time at which conditions

changed to permit the accumulation of ice in the North there must have been a considerable time lag between the actual beginning of glaciation and any evidence of it in the plains. Therefore, if the beginning of Blancan time coincides with the beginning of the ice accumulation the early part of that time was most likely warm, in the plains region, and evidence of climatic change would not be expected in the earlier faunas.

SUMMARY

In summary I believe the sequence of events may have been as follows:

At the close of Hemphillian times some major geological event took place which had the following effects: (1) extinction of a large number of Pliocene mammals, (2) the elevation of land connections between North America and Asia and between North America and South America, and perhaps general elevation of much of North America, (3) the introduction of conditions that permitted ice to accumulate to the extent that glaciers were able to spread from the various northern centers. These effects resulted in the introduction of the Blancan fauna to North America—a mixture of Asiatic, South American, and indigenous forms. In the early part of the Blancan a temperate and perhaps not too moist climate prevailed, but as the glaciers spread southward toward the climax of the Nebraskan advance boreal elements appeared in the plains faunas. The climax of the Nebraskan advance brought conditions that were too severe for *Nannippus*, *Plesippus*, and *Borophagus*, and their extinction was the result. Shortly thereafter the mammoths, *Bison* and other large artiodactyls, animals that may have begun their trek at the beginning of the Blancan, reached the plains and introduced the fauna that is characteristic for the rest of the Pleistocene.

PLEISTOCENE MAMMALS AND TERRACES IN THE GREAT PLAINS[1]

BY C. BERTRAND SCHULTZ AND THOMPSON M. STOUT

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ABSTRACT

The Pleistocene mammals of the Great Plains are in general rather easily differentiated (on the basis of morphologic changes as well as unquestioned stratigraphic occurrence) into at least five distinct faunal stages best expressed as Early, Medial, Late, Very Late Pleistocene, and Recent.

The recognition of the faunal stage of the Broadwater and Lisco fossil quarries in western Nebraska as Early Pleistocene rather than Late Pliocene is based upon several considerations. A faunal and stratigraphic break of great importance separates these deposits from the underlying Upper Pliocene (Ogallala Group, Kimball-Sidney) of the region. The faunal assemblage of the Sidney and Kimball sediments (Oshkosh quarries and related deposits) in this same region is unquestionably Pliocene, by any definition of the term, and the mammals are more advanced than those found in the underlying Ash Hollow formation. The mammals from the Broadwater and Lisco sediments are definitely more closely related to the Medial Pleistocene forms from Hay Springs and Rushville than they are to those of the Kimball-Sidney level. Also, if the Pleistocene be defined as the "Glacial Epoch," present stratigraphic evidence in Nebraska seems to demonstrate that the Broadwater and Lisco sediments are Pleistocene and that the Lisco member is equal at least in part to the Fullerton (Aftonian) of eastern Nebraska.

The terraces and related sediments of the Great Plains are discussed in some detail insofar as they date the fossil mammal occurrences and aid in showing the relation to the general Pleistocene stratigraphic, faunal, and climatic record. The cyclic nature of these Pleistocene sediments is stressed and utilized in classification.

INTRODUCTION

The Pliocene-Pleistocene boundary, in common with other geologic rock and temporal boundaries, has long been a subject of discussion among geologists and paleontologists. Unlike other boundary disputes, the original definitions of the units are not necessarily in conflict with the evaluating criteria. However, far more important than further discussion of these is the understanding of the stratigraphic and faunal records in the vicinity of this boundary.

It is felt that a rational approach to the general problems of this and related symposia requires a general presentation of the sedimentary and faunal succession within the Pleistocene of Nebraska and adjacent States in relation to the Late Tertiary history of the region. It is the plan and purpose of this paper to summarize briefly the stratigraphy and the faunas in the vicinity of the Pliocene-Pleistocene boundary (as understood in the Nebraska region), to relate this history to that of the Medial and Late Pleistocene, and finally to analyze the evidence presented insofar as it

[1] The sections of this paper set in small type, and the footnotes, were not read at the Symposium because of time restrictions; except for these elaborations of several important points, and the addition of Figure 3 (from Gignoux), no important changes have been made.

enables us to express an opinion concerning the placement of the beginning of the Pleistocene in the Great Plains and elsewhere.

The part of the Great Plains with which we are primarily concerned is strategically located in that both Pliocene sediments and Pleistocene tills (with related sediments) occur in the region. It has been for nearly a century the rich collecting ground and chief source of information regarding Medial to Late Tertiary and Pleistocene mammal development on this continent. Fossil mammal remains are now known from almost every 10 feet of sediment from the base of the Oligocene to the Recent (Pl. 1), so it appears necessary for clear thinking and further progress to have this record generally accepted by paleontologists and geologists as perhaps the only known complete (or even workable) standard for the continental Middle and Upper Tertiary of North America. Time terms for this part of the continental Tertiary which are not based upon this clear-cut and simple Great Plains rock record are confusing and must be eventually abandoned. Inasmuch as the continental Pleistocene succession beyond the till border is also complete, the writers believe that the sedimentary cycles of this region are of great importance in understanding and even in classifying the Pleistocene on this continent. It appears certain that the Pliocene-Pleistocene boundary dispute, in common perhaps with the Oligocene-Miocene and the Miocene-Pliocene boundary controversies, can be more nearly solved in the Nebraska-Kansas-South Dakota region than anywhere else in North America.

A general summary of the present classification of the Great Plains Tertiary and Pleistocene, particularly as used in Nebraska, is presented in Plate 1, and in more detail with regard to the Great Plains sedimentary cycles of the Pleistocene in Figure 4. Plate 1 is a photograph of a large pictorial wall chart which is on display in a corridor of the University of Nebraska State Museum in Lincoln. The painting includes restorations of some of the best-known fossil mammals, the skeletons or less complete specimens of most of these being featured in the exhibits of the University Museum.

It has been demonstrated (in Nebraska at least) during the last decade that fossil mammals are *practical* index fossils in nearly all instances where the lithologies of Tertiary sediments in the Great Plains have caused them to be confused with Pleistocene sediments. There appears to be no question but that at present the fossil mammals are far better age indicators and much more reliable than other fossil remains (including the fossil seeds of grasses and of borage herbs) found imbedded in these Pliocene and Pleistocene rocks. This is because of the rich stratigraphic collections of the fossil mammals, unequalled anywhere in the world, which have been obtained from these deposits.

Such large collections of fossil mammals are absolutely essential to an understanding of the range of individual, age, and sexual variation, as distinguished from geographic variation and phylogenetic change—all factors which must be considered before a specific or even a generic name can be correctly applied to a fossil specimen. Only by close study of large numbers of specimens from successive faunal levels or stratigraphically distinct channel fills and quarry sites is there any basis for reconstruction of phylogenies or for inference as to probable genetic modifications. Precisely collected fossil specimens are thus the vital documents which afford the paleontologists their only valid basis for understanding the "evolutionary process" or for

forming sound judgments (with use of statistical aids if desired) instead of speculating about fossil specimens.

A systematic stratigraphic and regional approach to the study of fossil mammals of the Medial to Late Tertiary and Pleistocene of North America is relatively new, because the early workers felt that the specimens themselves were adequate without any other data to show the vertical changes and to demonstrate the "evolution" in which they were primarily interested. The precise stratigraphic technique in collecting, as long employed by the invertebrate paleontologists, is thus a late outgrowth based upon the reconnaissance studies of the pioneer vertebrate workers. Let us consider how this stratigraphic approach aids in clarifying the problems which are now before us.

ACKNOWLEDGMENTS

Encouragement of a geologic approach to the study of the Pleistocene mammals, as a supplement to a morphologic analysis of the specimens, has been given by Mr. Childs Frick, Dr. Erwin H. Barbour, and a number of other paleontologists and geologists. Among these latter are Dr. Kirk Bryan, Dr. G. E. Condra, Dr. Maxim K. Elias, Mr. Charles H. Falkenbach, Mr. Weldon D. Frankforter, the late Dr. Edgar B. Howard, Dr. Gilbert C. Lueninghoener, Dr. A. L. Lugn, the late Prof. Henry Fairfield Osborn, Dr. Paul MacClintock, Prof. E. C. Reed, Prof. E. F. Schramm, Mr. Morris F. Skinner, and the late Dr. William J. Sinclair. To all of these colleagues the writers are much indebted. Also, a number of local collectors have materially assisted in helping to make known the rich record of Pleistocene mammal life in Nebraska and adjacent States: the late Mr. Sidney R. Sweet, Mr. T. C. Middleswart, Mr. W. F. Chaloupka, Mr. Russell Langford, and Mr. Lester Truescott. For all this help the writers wish to express their sincere thanks.

It may be of interest to mention that some 15 years ago Dr. William J. Sinclair of Princeton University predicted to the writers that it would be 20 years before a stratigraphic sequence of fossil mammals in the North American Pleistocene would be accepted. He further remarked that any attempts in that direction would be pioneer efforts. It now appears that a mammalian succession based upon a definite Pleistocene stratigraphic record and general chronology is approaching a reality.

KIMBALL-SIDNEY SEDIMENTS AND MAMMALS

The youngest Ogallala sediments of the Great Plains constitute the Kimball formation, with the Sidney gravel and silt member at the base locally unconformable on older beds, but generally affording a transition from the latest Ash Hollow sand and gravel channels. A determined search to find fossil mammal remains in sediments named Kimball and Sidney by Lugn (1939a) was started as early as 1934 by the University of Nebraska State Museum field parties. This search was successful, and the discovery was announced by the writers in 1940. The published abstract of this paper (Schultz and Stout, 1940b) stressed the importance of the lithologic and faunal break between the Kimball formation and the earliest terrace deposits (named the Broadwater formation by the writers in 1945) in western Nebraska. Later work has merely emphasized the importance of this break.

A partial list of the Kimball-Sidney mammals is given in Table 1. As pointed out in 1940, the mammals found in the Kimball-Sidney sediments are of a distinctive Pliocene type (closely related to those found in the underlying Ash Hollow formation), and they differ markedly from the mammals found in the later Broadwater-Lisco deposits of the same area. Such Pliocene mammals as rhinoceroses, longirostrine mastodonts, antilocaprids (*Texoceros*), and the advanced *Neohipparion* horse are characteristic of the Kimball-Sidney level. The connection of North America with South America, rather definitely completed at least by Ash Hollow time, is shown by the presence of the small ground sloth, *Megalonyx*. The most important element in the assemblage, however, is the horse identified as an advanced *Pliohippus* or primitive *Plesippus*, which is a sort of "connecting link" in the understanding of the development of the horses in the Great Plains.

The faunal break in the Great Plains is definitely between the Kimball-Sidney deposits (and equivalents) and the Broadwater-Lisco deposits (and equivalents). At the Broadwater-Lisco quarry level rhinoceroses are absent; only the short-jawed (brevirostrine) mastodonts *Stegomastodon* and *Mammut* (*Pliomastodon*) so far have been found at this level in the western Nebraska area, and the principal horse is the true *Plesippus* (primitive *Equus*). Some hold-over forms from the Pliocene also are to be noted, but this is to be expected and should not be stressed. A measure of the time gap between these two sets of sediments is furnished by the change from the primitive *Plesippus* of the Kimball-Sidney (as noted above, it is a form transitional from the Ash Hollow *Pliohippus*) to the true *Plesippus* of the Broadwater-Lisco level. All evidence considered, this time interval would appear to be not quite as long as the time which elapsed between the Broadwater and Hay Springs assemblages (to be discussed more fully later in this paper), or between Early and Medial Pleistocene.

The principal quarry sites in the Kimball-Sidney sediments in western Nebraska are south of Oshkosh, in Garden County, Nebraska. Upon the occasion of the First Field Conference of the Society of Vertebrate Paleontology, attended by most of the American students of fossil mammals (held in Nebraska in August and September, 1941), the writers had the pleasure of conducting the conference party to these Upper Pliocene quarry sites. The guidebook account of the quarries is quoted below:

"These quarries were first opened in 1937 by members of the University of Nebraska State Museum field party, assisted by S. R. Sweet, T. C. Middleswart, W. F. Chaloupka, and Lester Truscott. This and subsequent work has revealed an extremely interesting faunal assemblage of probable late Pliocene age. These sites are believed to be in the Sidney gravels, and a part of the Kimball formation is in place above. These quarries are some of the most important yet discovered in Nebraska and work is being continued to recover more of the fossil remains here" (Schultz and Stout, 1941, p. 15).

Several other sites (not included in the faunal listing of Table 1) are now known in rocks of this age in western Nebraska. Further exploration of these will be carried on during the 1947 field season.

In south-central Nebraska one locality of especial importance with regard to the Kimball-Sidney mammals should be mentioned. North of Cambridge, along Medicine Creek, in Frontier County, Nebraska, is the locality which yielded the famous type specimen of the shovel-tusked mastodont, *Amebelodon fricki* Barbour. The University of Nebraska State Museum has been engaged in the intensive study of

TABLE 1.—*Preliminary list of mammals from Kimball-Sidney sediments (Upper Pliocene) of Nebraska, not including those from Frontier County localities*

Garden County locality Gd-10 refers to the Oshkosh fossil quarries, south of Oshkosh, Nebraska. Morrill County localities Mo-8 and Mo-9 refer, respectively, to a locality south of Bridgeport, Nebraska, and to the *Sphenophalos* site northwest of Bridgeport. Cheyenne County localities Cn-11 and Cn-12 refer to the Dalton fossil quarries, near Dalton, Nebraska. A prospect site is included with the listing of the latter locality.

	Kimball formation				
	Sidney Gravel member				Upper part
	Garden County	Morrill County	Cheyenne County		Morrill County
	Gd-10	Mo-9	Cn-11	Cn-12	Mo-8
EDENTATA					
Megalonyx sp. (Small Ground Sloth)	—				
LAGOMORPHA					
Hypolagus? sp. (Rabbit)	—				
RODENTIA					
Sciurid (Citellus group) (Ground Squirrel)				—	
Sciurid (Cynomys group) (Prairie Dog)	—				
CARNIVORA					
Canid, undetermined (Coyote or Wolf)	—				
Carnivore, undetermined (Carnivore)	—				
PROBOSCIDEA					
Mastodont (Mastodont)	—				
PERISSODACTYLA					
Rhinocerotid, cf. Teleoceras (Rhinoceros)	—	—	—		—
Neohipparion sp. (Hipparion-like Horse)	—	—			—
Advanced Pliohippus or Plesippus sp. (Horse)	—			—	
Nannippus sp. (Small Horse)	—				
ARTIODACTYLA					
Prosthennops sp. (Peccary)	—				
Camelid, Giant Form (Giant Camel)	—		—	—	
Camelid, Small Form (Small Camel)	—		—		
Cervid, undetermined (Deer-like Form)	—				
Texoceros guymonensis Frick, ref. (Antilocaprid)	—				
Sphenophalos middleswarti Barbour & Schultz (Pronghorn)		—			

this locality, and of the rich collection of fossil mammals from it, since 1927. Field observations in 1933 and in later years by the writers, and in 1946 by Schultz and Frankforter, confirm the fossil evidence to suggest that the *Amebelodon fricki* and associated mammals come from a Sidney gravel equivalent rather than from the lower faunal level of this locality (upper part of the Ash Hollow formation).[2]

[2] The recently announced discovery of a specimen of *Amebelodon fricki* in Texas (Gregory, 1945) is of considerable importance from the standpoint of precise regional correlation. Also the discovery announced by Sellards (1940b; 1940a) of the unique mastodont *Gnathabelodon* (probably a descendant of *Megabelodon*) in the Goliad formation of the Texas Coastal Plain is important. Correlation thus would appear to be rather definitely established between this Bee County, Texas, locality and the spot in Trego County, Kansas (of uncertain age, Ash Hollow-Kimball), which yielded the first *Gnathabelodon* material (Barbour and Sternberg, 1935; Osborn, 1936, vol. 1, p. 710-714). A recent study of the Goliad includes a reference to the Bee County discovery (Weeks, 1945b).

THE LITHOLOGIC BREAK

Throughout the Medial and Late Tertiary and the Pleistocene, just as today, the Great Plains (especially the High Plains) seem to have constituted a physiographic unit. Periods of erosion and aggradation seem to have been regional rather than localized in their effects, apparently responding to widespread diastrophic and perhaps also climatic controls. Four major sedimentary cycles, each bounded above and below by important unconformities (probably caused by major uplift in the Rocky Mountains since folding and faulting accompanied at least one of these breaks), allow the Great Plains Tertiary deposits to be divided into four groups: the White River, Arikaree, Hemingford, and Ogallala groups (Lugn, 1939a) (Pl. 1). Within each group the formations and members are separated by less important unconformities accompanied by lithologic differences. These major and minor unconformities reflect faunal breaks of approximately the same magnitude.

The Ogallala group, as now understood by the writers and their colleagues, is believed to represent the entire Pliocene, with the Kimball-Sidney sediments at the top, overlying the Ash Hollow and Valentine formations (Pl. 1). These formational and member divisions of the Ogallala are prominently developed in Nebraska and northeastern Colorado, as well as in South Dakota. It may be possible eventually to trace and map these Ogallala units in detail from South Dakota to Texas, but such detailed stratigraphic correlations would be virtually impossible without the supplementary dating and confirmatory check provided by the fossil mammals.

At the end of Ogallala (Kimball) time, an almost flat or featureless aggradational plain, representing the culmination of the long period of Tertiary aggradation in the Great Plains, covered most of southwestern Nebraska, perhaps western Kansas, and the panhandles of Oklahoma and Texas. According to Frye (1946b, p. 78):

> "At the close of Ogallala deposition, an alluvial constructional plain of low relief sloped eastsoutheastward across this region [southwestern Kansas], but little if any of this plain is preserved in the present topography."

The characteristic flat prairie and table land areas of a considerable part of southwestern Nebraska (High Plains) are today upheld by the resistant algal (*Chlorellopsis*) limestone (Elias, 1931; Lugn, 1939a) or by the caliche layers, diatomaceous marl, and Sidney gravel member of the Kimball formation. Where aggradation and local ponding (to produce the limestone) were impossible, pedimentation appears to have been a dominant process. This was probably the situation in the Big Badlands of South Dakota, where the summit pediment surface seems to have been developed at this time (Schultz and Stout, 1945, Pl. 2, fig. 3). This prominent gravel-veneered pediment, which has been called the "Upper Prairie" by Ward (1922), has been traced by the writers from the Big Badlands far south into northern and northwestern Nebraska. The gravels which mantle this pediment in the Big Badlands northwest of Interior, South Dakota, would appear to correlate with the Broadwater formation (T^5 or Terrace 5 of the writers' terminology; *see* Figure 4), and the relation to the later terraces of the Big Badlands (intensively studied by the writers and their associates over a period of many years) appears to substantiate this correlation. Although no

fossils so far have been recovered from these high gravels, their eventual discovery is to be anticipated.[3]

Following this development of the Kimball plain, there began in western Nebraska and immediately adjacent region a period of major degradation, which, with less significant aggradational interruptions, has continued to the present. It is this dominant downcutting which has been responsible for exposing most of the Tertiary and older sediments of the region, but it affords a sharp contrast with the dominantly aggradational history of central and eastern Nebraska during the Pleistocene (Lugn, 1935).

The Pleistocene alluvial terraces and fills of western Nebraska are to be found in high (oldest) to low (youngest) positions along the walls and slopes of the river valleys in a normal alluvial terrace arrangement (Schultz and Stout, 1945, Fig. 2), but in eastern Nebraska the oldest fills have been buried under successively younger fills. The transition between this degrading and aggrading Pleistocene is well shown in the vicinity of Paxton (the Paxton Cut) in Keith County, Nebraska, where the base of the oldest terrace fill (Broadwater formation) along this section of the North Platte River approaches water level in the divide ridge between the present North and South Platte rivers. Only a short distance east or southeast of the Paxton Cut the equivalents of this oldest terrace fill (Broadwater formation) appear to go completely into the subsurface, being buried eastwardly and southeastwardly by the later Pleistocene sediments. However, times of alluviation in western Nebraska appear in general to have been also times of alluviation in central and eastern Nebraska, and the same equivalence seems to hold for times of erosion during the Pleistocene.

The time of initial cutting into the Tertiary after Kimball time, as described above, marks the beginning of the history of the North Platte River in approximately the same course as at present for that part of the river west of Bridgeport, Nebraska. This may allow a more accurate dating as well as present new evidence to support the hypothesis advocated by Atwood and Atwood (1938b, p. 968, 970–971) regarding the time of initial superposition of the North Platte and other major drainage lines in the Rocky Mountain region.[4]

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[3] It is quite possible that there is an equivalent of this "Upper Prairie" pediment and its gravel capping along the eastern slope of the Black Hills, but it has not been clearly distinguished. Presumably it would be lower topographically than the pediment termed "Mountain Meadow Surface" by Louise Fillman (1929). The latter surface is clearly of pre-Chadron (pre-Lower Oligocene) age (rather than pre-Brule or pre-Middle Oligocene as dated by Fillman), since it seems to be mantled by the basal Chadron conglomerate and some younger sediments. Fillman (1929) correlated the "Upper Prairie" pediment of Ward (1922) with her "Rapid Terrace" or "Rapid Formation", the next level that she recognized below the "Mountain Meadow" along Rapid Creek, a tributary of the Cheyenne River east of Rapid City, South Dakota. However, reconnaissance field studies by the writers in 1936 (and later) suggest as a more likely correlation that the "Rapid Terrace" of the Cheyenne River equals the T^3 or Second Terrace of the White River, and that Fillman's "Sturgis Terrace" on the Cheyenne equals the T^1 or First Terrace of the White, whereas the "Upper Prairie" is the high level surface (T^5?) in the eastern Big Badlands. A full development of the terraces is to be seen near Interior, South Dakota, but only those terraces after T^2 time are related to the present White River; those earlier than the T^2 valley fill were apparently part of a drainage direct from the Black Hills (Wanless, 1923, p. 264–269, Fig. 10) as is demonstrated by gravels of Black Hills origin on the south side of the present White River in the T^3 valley fill (Schultz and Stout, 1945, Pl. 2, fig. 3). At the time of deposition of the T^2 valley fill, the Hat Creek headwaters of the present Cheyenne River in northwestern Nebraska and eastern Wyoming were almost certainly tributary to a White River which otherwise had its present course. The present upper headwaters (Hat Creek) of the Cheyenne thus appear to have been acquired by the Cheyenne after T^3 time.

[4] This superposition and downcutting were supposedly inaugurated by uplift at about this time in the region to the west of the Great Plains (Mackin, 1937, p. 823; Atwood and Atwood, 1938a, p. 247; Mather, 1925; Van Tuyl and Lovering,

BROADWATER-LISCO SEDIMENTS AND MAMMALS

The Broadwater locality, in western Nebraska along the north side of the North Platte River (Fig. 1), was discovered 10 years ago (Barbour and Schultz, 1936; 1937a). It has been worked intensively since that time by University of Nebraska State Museum expeditions, by several assisting local collectors (the late S. R. Sweet, together with T. C. Middleswart and W. F. Chaloupka), and with Works Projects Administration aid during several years in both field and laboratory. The workings here, and at some of the neighboring Lisco sites, represent some of the most extensive quarries ever opened for the extraction of fossil remains. As a result of these operations, there has been assembled at the University of Nebraska State Museum the largest known collection of fossil mammal remains from rocks of this age.

The Broadwater formation was named by the writers in 1945 (Schultz and Stout, 1945), with differentiation of a basal gravel member, a middle member (designated the Lisco member) of diatomaceous marl-peat and associated silts, and an upper gravel member. The formation appears to have been deposited in part in an ancestral North Platte River valley, and in contemporaneous valleys, cut rather deeply into the Ogallala deposits (Schultz and Stout, 1945, Fig. 2). There is probably no question but that uplift of the aggradational plain of late Kimball time, or (and) of the mountains to the west, caused the ancestral North Platte River and contemporaneous streams to cut these valleys in pre-Broadwater time.

The Broadwater formation constitutes the terrace fill of the fifth terrace (T^5) above the flood plain of the present North Platte River, and it has been traced from near Bridgeport and other points westward to Scottsbluff (Schultz and Stout, 1945, Fig. 2), where it has been found to be the same as the "Terrace Hills" of Dow and Lugn (Lugn, 1935). The recent comprehensive Water Supply Paper 943 of the United States Geological Survey (Wenzel, Cady, and Waite, 1946) has applied the writers' terrace terminology to the terraces of the Scottsbluff area. As pointed out to Cady by the writers in several field conferences, the oldest post-Ogallala terrace in this area is the fifth terrace (T^5), and the so-called "older terraces" of Cady are clearly not Pleistocene but appear to be residual and slump surfaces developed on Ogallala ("Upper Snake Creek" or Ash Hollow, and some Sidney) gravels and so can hardly be considered as terraces at all.

The Lisco member (Schultz and Stout, 1945, Fig. 2) is the level within the Broadwater formation which has yielded most of the fossil mammals so far collected from these beds. It now seems very likely that this is the more or less exact stratigraphic equivalent of the Fullerton formation (Aftonian) of eastern and central Nebraska.

1935, p. 1326, 1335–1336; Love, 1939, p. 113–117; Bradley, 1936, p. 177–199; Behre, 1933, p. 813–814; and Powers, 1935). A discussion of the problem involved in correlating the Ogallala deposits of the Great Plains (western Kansas and eastern Colorado) with Ogallala remnants in the mountains to the west is given in a paper by H. T. U. Smith (1940, p. 92–94). However, the dating of the mountain pediments and related sediments is difficult, since it involves working backward by means of the terraces and mountain glaciation (Bryan and Ray, 1940; Ray, 1940) as well as forward from Ogallala remnants. Studies in South Park, Colorado (Stark *et al.*, 1936), are of unusual importance because of the relation to the time of incision of the present South Platte River; the drainage of South Park was originally south, but uplift "dated by the age of the latest beds truncated by the old Badger Creek surface" favored the South Platte in cutting across the Front Range. It has been pointed out by the writers (Schultz and Stout, 1945, p. 236) that the Broadwater formation constitutes the high-level terrace (T^5) along the South Platte near Chappell, Nebraska, and the South Platte (and Cache la Poudre) terraces identified by Bryan and Ray (1940) and Ray (1940) in terms of pediments and mountain glaciation have been correlated with the terrace terminology used in the present paper (Fig. 4).

FIGURE 1.—*Broadwater and Lisco fossil localities (Lower Pleistocene), in Morrill and Garden counties, western Nebraska*

The quarry sites occur in the Lisco member of the Broad water formation, between the basal and upper gravel members of this formation. The Lisco member may be the more or less exact stratigraphic equivalent of the Fullerton formation (Aftonian) of eastern and central Nebraska. The Lisco member at the Broadwater localities is situated between 445 and 465 feet above the present North Platte River, whereas at the easternmost Lisco localities it occurs at a level between 380 and 400 feet above the present river. At the Broadwater sites an ancient stream-side river habitat is sampled, while at the Lisco sites the sediments are colluvial and loess-like silts, and the mammals are chiefly upland types. The Oshkosh sites (Upper Pliocene), mentioned in the text, are situated a few miles southeast of this map area.

At the Broadwater sites the Lisco member consists of a marl-peat bed between the lower and upper gravel members of the formation, but at the Lisco localities to the east (Fig. 1) the fossils are found in colluvial and alluvial silts as well as in loesslike silt and fine sand. Although all sediments of the Lisco member are roughly contemporaneous, since the entire member is situated between the two gravel sheets, there is a possibility (now being investigated) that the loesslike and related colluvial-alluvial silts are not precisely contemporaneous with the marl-peat bed. This may have some interesting climatic implications, as noted below.

There are pronounced faunal differences between the fossil mammals found at the several localities (Table 2). There is no question but that at the Broadwater sites a stream-side river habitat is sampled, while at the various Lisco sites the faunal elements indicate largely upland or prairie types such as would come to water at a small tributary stream.[5] It should be pointed out that these faunal differences are almost precisely what have been termed in Europe (by Penck adherents) the "warm" fauna as contrasted with the "cold" or "steppe" fauna. Although only habitat differences can be safely inferred from the fossil evidence in most situations of this type, European workers have almost invariably accepted such distinctions as due to temperature controls.

SEDIMENTS AND MAMMALS AT HAY SPRINGS-RUSHVILLE-GORDON-MULLEN

Near Hay Springs, Rushville, and Gordon, in Sheridan County, and near Mullen, in Cherry County, Nebraska, there occur Middle Pleistocene fossil quarries which have yielded the largest known collections of fossil mammals from rocks of this age in North America (Table 3). These sediments and their contained mammals were considered by Matthew as late as 1929 (Matthew, 1929, p. 438–441, 530) to be of Early Pleistocene age, but such a dating is impossible now that the deposits can be rather precisely correlated.

The first geological work and collecting in this general region was by F. V. Hayden on the 1857, expedition under the direction of Lieutenant G. K. Warren of the U. S. Army Engineers. The expedition travelled up the Loup and Middle Loup rivers, passed the present sites of Seneca and Mullen in Thomas and Hooker counties, and then followed the North Prong of the Middle Loup to its head, through southwestern Cherry County. From these headwaters, the expedition cut across the sand hills to the Niobrara River, reaching it near the present Hay Springs fosssil quarries. A detailed study of the expedition's records preserved in the National Archives and elsewhere is under way by W. D. Frankforter and the writers, but the general itinerary is shown on Hayden's map (Leidy and Hayden, 1869). Presumably between the dates of July 30 (near Halsey) and August 10, 1857 (at the Niobrara), were collected most of the "Loup River" fossils later described by Leidy (1869 and earlier papers), although some of the descriptions of these were confused with specimens collected on the return trip down the Niobrara later in the same season. The fossils which appear to have been collected from the vicinity of the present Mullen fossil quarries include the fragmentary holotypes of *Archidiskodon imperator* (Leidy), *Equus excelsus* Leidy, and *Panthera augustus* (Leidy). The holotype of *Stegomastodon mirificus* (Leidy) rather definitely came from older beds, from some unknown outcrop of the Lower Pleistocene Broadwater equivalent. The Middle Pleistocene descendant of *Stegomastodon mirificus* is apparently the *S. aftoniae*, a species with a more wrinkled trefoil dental pattern.

[5] This was discussed in papers presented at several national meetings in 1939 and 1940 (Schultz and Stout, 1939, 1940a; 1940b).

TABLE 2.—*Revised list of mammals from Broadwater-Lisco sediments (Lower Pleistocene) of Nebraska, not including those from eastern Garden County, Brown County, or central and eastern Nebraska localities*

Compare with Schultz and Stout, 1941, Table 3. Morrill County localities Mo-5, 6, and 7 were previously termed "Broadwater Locality A"; Garden County locality Gd-11 was earlier referred to as "Lisco Locality A"; Garden County locality Gd-12 was called "Lisco Locality B"; and Garden County localities Gd-13, 14, and 15 were designated "Lisco Locality C". These localities (and fossil quarries) are shown on Figure 1. The mammals of the marl-peat facies (at the Broadwater locality) are regarded as definitely demonstrating a stream-side river habitat (frogs are abundant, and there are numerous aquatic or stream-side river forms), while those of the colluvial and loesslike silt facies (at the Lisco localities) appear to be "upland" or prairie or steppe mammals.

	Broadwater formation, Lisco member			
	Marl-peat facies	Colluvium-"loess"		
	Morrill County	Garden County		
	Mo-5, 6, 7	Gd-11	Gd-12	Gd-13, 14, 15
INSECTIVORA				
Sorex sp. (Shrew)	—	—	—	—
EDENTATA				
Paramylodon sp. (Ground Sloth)	—	—	—	—
Megalonyx sp. (Ground Sloth)	—	—	—	—
LAGOMORPHA				
Lepus or Hypolagus sp. (Rabbit)	—	—	—	—
Sylvilagus sp. (Rabbit)	—	—	—	—
RODENTIA				
Sciurid (Citellus group) (Ground Squirrel)	—	—	—	—
Sciurid (Cynomys group) (Prairie Dog ?)	—?—	—	—	—
Marmota sp. (Woodchuck or Marmot)				—
Dipodomys sp. (Kangaroo Rat)				—
Geomys quinni McGrew (Eastern Pocket Gopher)	—	—	—	
Geomys sp. (Eastern Pocket Gopher)	—	—	—	
Thomomys sp. (Western Pocket Gopher)	—?—			
*Procastoroides sweeti Barbour and Schultz (Giant Beaver)	—	—	—?—	
Castoroides? sp. (Giant Beaver)	—	—	—	
Small Beaver (Extinct Beaver)	—	—	—	
Peromyscus sp. (White-footed Mouse)	—	—	—	
Neotoma? sp. (Wood Rat)	—	—	—	
**Pliopotamys meadensis Hibbard (Muskrat)	—	—	—	
***Pliophenacomys primaevus Hibbard (Vole)	—	—	—	
? Ogmodontomys poaphagus Hibbard (Vole)	—	—	—	
Pliozapus? sp. (Jumping "Mouse")	—	—	—	
CARNIVORA				
Canis sp. (Coyote)	—	—	—	—
Borophagus sp. (Extinct Wolf)	—	—	—	—
Satherium piscinaria middleswarti Barbour & Schultz (Otter)	—	—	—	—
Mephitis sp. (Skunk)	—	—	—	—
Smilodon sp. (Sabre-tooth Tiger)	—	—	—	—

TABLE 2.—*Continued*

	Broadwater formation, Lisco member			
	Marl-peat facies	Colluvium-"loess"		
	Morrill County	Garden County		
	Mo-5, 6, 7	Gd-11	Gd-12	Gd-13, 14, 15
PROBOSCIDEA				
Stegomastodon mirificus (Leidy) (Short-jawed Mastodont)				
Mammut (Pliomastodon) sp. (Ancestral American Mastodont)				
PERISSODACTYLA				
Plesippus simplicidens (Cope) (Horse)				
Equid (near Nannippus) (Small Horse)				
ARTIODACTYLA				
Platygonus sp. (Peccary)				
Camelops sp. (Camel)				
Tanupolama sp. (Llama)				
Gigantocamelus fricki Barbour & Schultz (Giant Camel)				
Capromeryx arizonensis schultzi Skinner (Subpronghorn)				

* Synonym: *Eocastoroides lanei* Hibbard.

** Synonym: *Neondatra kansasensis* Hibbard.

*** This is of the same general type of microtine as the well-known but somewhat controversial *Mimomys*, described from England and Eurasiatic Villafranchian deposits (but not limited to the Villafranchian, according to Schaub, 1944); the American subgenus is *Cosomys* (Wilson, 1932; 1933; 1937), which may be ancestral to voles of the *Pedomys haydeni* group. It is possible that *Pliolemmus antiquus* Hibbard is the young animal of the present species.

The term "Loup River Beds" was given by Meek and Hayden (1861, p. 435, table on p. 433) to the beds investigated by the 1857 expedition which yielded the fossils noted above. Unfortunately, the faunal listings included some specimens from the Niobrara collected later in the season from the Pliocene beds. This may have caused Cope and others to use the synonymous term "Loup Fork" for Pliocene beds throughout western North America, but in a restricted sense the "Loup River" would refer to the Middle Pleistocene deposits studied by Hayden and Warren along the North Prong of the Midde Loup River (Osborn and Matthew, 1909, p. 83–84; Schultz, 1934, p. 357, 365).

The Yale College expeditions of 1870 and 1873, under the direction of Professor O. C. Marsh, collected on the North Prong of the Middle Loup. The 1870 expedition collected among other specimens later made types the holotype of "*Bison ferox*" Marsh, now considered (Schultz and Frankforter, 1946, p. 5) to be synonymous with *Bison* (*Superbison*) *latifrons* (Harlan).

The next collecting in this region was by Samuel Garman in 1880, who collected from the Sheridan County deposits the type specimen of the Ground Sloth "*Mylodon garmani*" Allen (1913), now regarded by the present writers as synonymous with *Paramylodon nebrascensis* Brown (1903).

Following Garman, John Bell Hatcher explored the Sheridan County deposits in 1886 and 1893. As a result of Hatcher's work, Scott (1897) gave the name of "Sheridan beds" for what he had previously (1894) called "*Equus* beds."

The American Museum of Natural History expeditions of 1893, 1897, and 1916 conducted minor quarry operations south of Hay Springs, but the exact locations of these quarries cannot now be determined. Yale University also made a small excavation in the area in 1915. The present Hay

TABLE 3.—*Revised list of mammals from the Sheridan County localities (Middle Pleistocene) of Nebraska*

Compare with Schultz and Stout, 1941, Table 4. Sheridan County locality Sh-1 refers to the main fossil quarries south of Hay Springs, Nebraska; Sh-9 is the near-by Yale University excavation of 1915; Sh-3 and Sh-4 are the Rushville fossil quarries, south of Rushville, Nebraska; and Sh-5 and Sh-6 are the Gordon fossil quarries, south of Gordon, Nebraska. Most of the fossil mammals from these localities and quarry sites have come from the Grand Island gravels, which occur stratigraphically below the marl and peat bed of the Upland formation and the lens of Pearlette ash (Fig. 4).

	Grand Island (and Upland) formations		
	Sheridan County, Nebraska		
	Sh-1, 9	Sh-3, 4	Sh-5, 6
INSECTIVORA			
Sorex? sp. (Shrew)			
EDENTATA			
*Paramylodon nebrascensis Brown (Ground Sloth)			
Megalonyx leidyi Lindahl (Ground Sloth)			—?—
LAGOMORPHA			
Lepus sp. (Rabbit)			
RODENTIA			
Sciurid (Citellus group) (Ground Squirrel)			
Cynomys niobrarius Hay (Prairie Dog)			
Dipodomys sp. (Kangaroo Rat)			
Geomys sp. (large) (Eastern Pocket Gopher)			
Geomys sp. (small) (Eastern Pocket Gopher)			
Castoroides? nebraskensis (Barbour) (Giant Beaver)			
Castoroides sp. (Giant Beaver)			
Castor sp. (Beaver)			
Peromyscus sp. (White-footed Mouse)			
Ondatra nebrascensis (Hollister) (Muskrat)			
Microtine, undetermined (Vole)			
CARNIVORA			
Canis sp., near C. latrans Say (Coyote)			
Canis (Aenocyon) dirus nebrascensis Frick (Wolf)			
Urocyon? sp. (Gray Fox?)			
Arctodus simus nebrascensis Frick (Giant Bear)			
Procyon sp. (Raccoon)			
Mustela sp. (Weasel)			
Smilodon nebrascensis Matthew (Sabre-tooth Tiger)			
Panthera sp. (Leopard-like Cat)			
PROBOSCIDEA			
Archidiskodon imperator (Leidy) (Imperial Mammoth)			
PERISSODACTYLA			
Equus excelsus Leidy (Horse)			
Equus calobatus nebrascensis Frick (Horse)			

TABLE 3.—*Continued*

	Grand Island (and Upland) formations		
	Sheridan County, Nebraska		
	Sh-1, 9	Sh- 3, 4	Sh- 5, 6
ARTIODACTYLA			
Platygonus vetus Leidy (Peccary)			
Camelops kansanus Leidy (Camel)			
Tanupolama americanus (Wortman) (Llama)			
Odocoileus sheridanus Frick (White-tailed Deer)			
**Capromeryx furcifer Matthew (Subpronghorn)			
Hayoceros falkenbachi Frick (Hay's Pronghorn)			
Hayoceros barbouri Skinner (Pronghorn)			
Bootherium sp. (Extinct Muskox)			

* Probable synonym: *Mylodon garmani* Allen.

** This is rather a common species in these quarries, despite some statements in the literature that this is an Ogallala form rather than Pleistocene. The holotype was from the American Museum of Natural History excavations of 1893 and 1897, and this specimen is just like other specimens recovered from the Middle Pleistocene deposits of this general area. *Capromeryx minimus* Meade, from Lubbock County, Texas, is an undoubted synonym. The recently proposed *Breameryx* Furlong appears to be invalid, being the same genus as *Capromeryx*, and established chiefly on the premise noted above.

Springs quarries were first opened and extensively worked by Charles H. Falkenbach from 1928 to 1930 for the Frick Laboratory, American Museum of Natural History (Frick, 1929; 1930), and were reopened by the University of Nebraska State Museum in 1940. The latter institution also conducted explorations in this area in 1901 and 1917. The Rushville fossil quarries, first a prospect discovered by Falkenbach, were worked by Nebraska field parties in 1932–1933, 1937–1938, and 1940. Quarries south of Gordon were worked from 1937 to 1939 and in 1941. The Work Projects Administration assisted in these large-scale quarry operations as well as with laboratory preparation during several of these years. The Mullen fossil quarries, of apparent similar age, were discovered in 1930 by Charles S. Osborn of the Nebraska expedition on the North Prong of the Middle Loup River, in southwestern Cherry County, Nebraska, and these have been extensively quarried since that time.

The sediments south of Hay Springs and Rushville appear to have been deposited in an ancestral Niobrara River valley, situated south of the present river valley and cut into the Ogallala bedrock. These deposits make up the terrace fill of the fourth terrace (T^4) as pointed out by the writers in 1945 (Schultz and Stout, 1945) and consist of a basal gravel (clearly the Grand Island, of possible late Kansan or Yarmouth age) from which the fossils have chiefly come, overlain by a fossiliferous marl-and-peat bed (the Upland, of possible Yarmouth age). The latter is succeeded by what appear to be two sets of sparingly fossiliferous gravels, one set of these being the newly defined Crete of Condra, Reed, and Gordon. The Loveland and "Peorian" loess sheets mantle the terrace fill and the T^4 surface. The Pearlette ash bed occurs as a lens near the 1915 Yale Quarry, in relation to the marl-peat bed and below the Loveland loess; nearly all the fossils in the area come from below the marl-peat bed and Pearlette ash, in the Grand Island gravels.

There is now no question as to the Medial Pleistocene age and exact stratigraphic

position of the fossiliferous beds in this area, but up to a very few years ago the literature always referred to these deposits as yielding the best-known "Early Pleistocene" or even "Upper Pliocene" fauna. (*See*, for instance, Osborn and Matthew, 1909, p. 83.) It was apparently at about the time of deposition of the Grand Island sediments that the Mammoth and Giant Bison (and other bovids) first reached the Great Plains. Size differences and definite vertical changes are very pronounced throughout the Pleistocene in many groups of mammals, but in most instances these size changes are progressive except for the example of retrogression recently demonstrated by Schultz and Frankforter (1946) for the horns of the bison of the Great Plains (Fig. 2).

The old dictum, "There is no evolution in the Pleistocene," has been proved wrong, but the basis for the concept was confusion produced by mixed faunas and inadequate stratigraphic data. For example, the old "Aftonian fauna" of Calvin (1909; 1910; 1911), Shimek (1909; 1910), and Hay (1914; 1923; 1924; 1927; 1925; 1928) was, unfortunately, totally misconceived, as noted by Barbour and Schultz (1937a); this faunal assemblage from western Iowa is largely of Late Pleistocene (probably Iowan) age rather than Early Pleistocene. Considerable time has been spent in the field by the writers and their colleagues in study of the valley fill and older sediments in the Cox and other gravel pits from which Calvin's collections were made, and these studies seem to substantiate this tentative age determination. Because of this confusion as to what constitutes an Upper Pleistocene fauna, it appears necessary to review very briefly here the results of recent work on the Upper Pleistocene sediments and mammals in the Great Plains.

UPPER PLEISTOCENE SEDIMENTS AND MAMMALS

The general summary chart shown here (Figure 4) includes a classification of the Upper Pleistocene terrace deposits and related sediments of the Great Plains (particularly for Nebraska), as recently discussed by the writers (Schultz and Stout, 1945). The cycles are based upon the stratigraphic and terrace-fill sequence, together with a general concept that the buried soils of the Pleistocene in this region can scarcely be interpreted otherwise than as the products of relatively humid and perhaps fairly warm conditions when vegetation and animal life flourished. The loess sheets, on the contrary, represent different climatic conditions, interpreted as chiefly products of prolonged droughts. A single terrace cycle begins with a cutting episode following the main soil development of the previous cycle, includes alluviation in valleys and loess deposition on the uplands, and major soil development concludes the cycle (Schultz and Stout, 1945, Fig. 4).

It is recognized that the terraces and terrace fills of separate drainages can be correlated without difficulty from South Dakota and eastern Wyoming to northern Texas, on both stratigraphic and paleontologic data which now have been accumulated. The faunal assemblage of the basal part of the second terrace (T^2) is distinctive, and the larger extinct animals usually are found associated with the Yuma-Folsom "index artifacts." There now can be no question as to the time of extinction of the larger North American mammals of the Pleistocene in the Great Plains—none of these extinct forms has ever been found above the lower to middle parts of the second terrace (T^2). The Recent fauna of the T^1 terrace fill is not distinguishable at present from that of the T^0 or flood-plain fill but

EPOCH	AGE	FORMATIONS MATERIALS
GLACIAL OR	RECENT	
		Terrace 1
	WISCONSIN — Cochrane	
		Terrace 2
	Mankato	Bignell loess
		Terrace 3
	Tazewell-Cary	Brady soil
		"Peorian" loess
	Iowan	
	SANGAMON	*Citellus* Zone soil
	ILLINOIAN	Loveland loess, Sand and gravel (Crete)

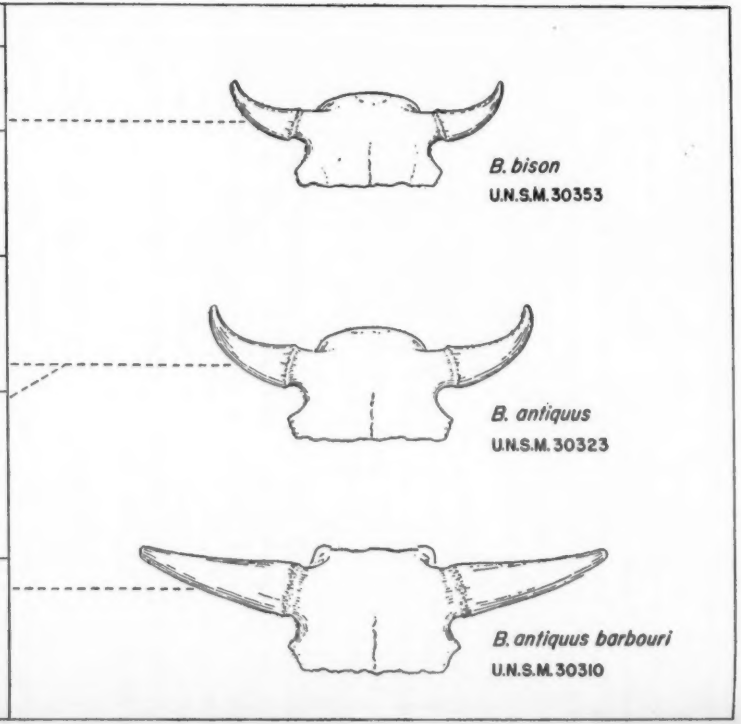


FIGURE 2.—*Geologic distribution of the bison of the Great Plains*
From Schultz and Frankforter (1946). The skulls were drawn by Nathan L. Mohler. X1/15.

when the large collections from these two sets of deposits and from Indian house sites are quantitatively compared some distinctions may be possible.

The names to be applied to the Pleistocene buried soils offer special difficulties but it should be noted that the names Sangamon, Yarmouth, and Peorian were first used and strictly defined by Leverett (1898a; 1898b; 1898c; 1898d) in a stratigraphic sense for the *buried soils* and immediately related sediments which he (correctly) interpreted as interglacial. Only later were these names extended to include the loess sheets and other materials. The presence of a soil within the so-called "Peorian" loess has been noted in the loess-canyon area in Lincoln County, Nebraska. The writers propose the name Brady soil for the 1.5-foot buried soil (chiefly the "A" horizon of this profile, previously termed Soil "X" by Schultz and Stout, 1945, Fig. 3) at the top of the "Peorian" loess and below the Bignell loess. The type locality is the same as that for the Bignell loess, named by the writers in 1945, namely, the Bignell Hill section, southeast of North Platte, 1.7 miles due south of Bignell, in the E1/2 of the E1/2 sec. 3, T.12 N., R.29 W., Lincoln County, Nebraska. The name "Sangamon" Soil possibly may be applicable in its strict stratigraphic sense to the *Citellus* zone soil, or a new name may be necessary for a more convenient and proper description of it. This may be also referred to as the "Loveland soil", although it may be developed on materials other than Loveland loess.

The basal part of the Bignell loess and the upper surface of the Brady soil appear to be approximately contemporaneous with the lower and middle parts of the second terrace fill (T^2) in western Nebraska and adjacent parts of the Great Plains. It is in the lower to middle parts of the T^2 terrace fill, on the upper surface of the soil on the "Peorian" loess (Brady soil, near Interior, S. D.), and in the upper part of the bluish-gray marl of the deeper Sand Hills blowouts (this marl correlated with the Brady), that Yuma-Folsom artifacts are commonly found associated with the remains of extinct mammals in many parts of the Great Plains. Thus, the time of first appearance of these "First Americans" in the Great Plains has been definitely determined in terms of the Great Plains Pleistocene sequence.

The time of extinction of the spectacular large Pleistocene mammals may possibly be related to the coming of Man to the New World as first pointed out by Schultz (1937). At any rate, insofar as the Great Plains are concerned this extinction occurred during the time of deposition of the lower to middle parts of the T^2 fill. The Pleistocene of the Great Plains may therefore be sharply separated from the Recent (much as in Europe) by this relatively sudden extinction, and it may be coincidence that this post-Mankato or post-Pomeranian time was apparently also the beginning of the final dissipation of ice in Europe, as well as similar supposedly correlative events in North America (Bryan and Ray, 1940, p. 55–67; Bryan, 1941b, p. 56–57; 1941a, Table 1).

Some interesting attempts at carrying back an exact chronology, from the present through the flood-plain fill (T^0) to the first terrace fill (T^1) in eastern (and western) Nebraska, have been published recently by Champe (1946). These archeological data, when considered with the Yuma-Folsom evidence and that derived from the mammals, allow considerable precision in the correlation of the terraces in Nebraska, western South Dakota, eastern Wyoming, and eastern Colorado (Fig. 4; Schultz and Stout, 1945; Bryan and Ray, 1940). The resulting late history of this region, including the physiographic history since about 1100 A.D., is very similar to that worked out by Hack (1945) for Arizona and by Bryan (1941c; 1941a) and his coworkers for New Mexico.

In this connection, special mention should be made of the usefulness and importance of the Yuma-Folsom "index" artifacts (with associated mammals) and of the terrace-fill sequence, in working out and correlating events in the late history of even distant parts of the continent. Thus, there seems to be no essential difference in the later terrace-fill history of northern Texas, of New Mexico, or of Arizona, when compared with that of the region farther north. There can be little question now as to the correlation of the T^2 or Kersey terrace fill of Nebraska, eastern Colorado,

western South Dakota, and eastern Wyoming (Schultz and Stout, 1945; Bryan and Ray, 1940) with the Neville-Jeddito terrace fill of the Southwest (Bryan, 1941a; 1941b; 1940; Bryan and Toulouse, 1943, Table 2; Albritton and Bryan, 1939; Hack, 1945; Evans and Meade, 1945, p. 500–502). Likewise, the T^1 or Kuner terrace fill of the northern region is surely the equivalent of the Calamity-Tsegi terrace fill of the Southwest. Also, there is essential synchroneity demonstrable in the T^0 or flood-plain history of the region to the north when comparison is made with the Kokernot-Naha or flood-plain fill of the Southwest. (*Note* particularly Bryan, 1941c, p. 228–229; 1940, p. 229; 1941a, reprint p. 23; and Hack, 1945.)

The discovery of Paleo-Indian artifacts and associated fossil mammals in the Berclair terrace of the Texas Coastal Plain, announced by Sellards, Campbell, and Evans (Sellards, 1940a), allows the very important extended correlation with the Coastal Plain terraces (also previously discussed by Bryan, 1941a, reprint p. 21–22). Since this Berclair terrace fill of Bee County, Texas, is directly traceable into at least a part of the Beaumont terrace (Sellards, 1940a) of the Coastal Plain, an important tie-in is established. Weeks (1945a, p. 1709, 1717) accepts the Beaumont age of this deposit in his comprehensive review of the Texas Coastal Plain terraces, but it would appear to the writers that this would mean that this part of the Beaumont is placed a little too low in the Wisconsin on his correlation table.

Sellards (1940a, p. 1650–1655) correlates the fossil mammals and artifact-bearing deposits of Bee County, Texas, with those of Ingleside, Texas, and with those of the well-known Melbourne bone bed of Florida. The Florida deposit has been recently placed in the Pamlico by Cooke (1945, p. 299–311), in his general review of the evidence for sea-level fluctuations in Florida during the Pleistocene. The Pamlico represents the 25-foot shore line (Cooke, 1945, p. 248) with only one later shore line, the 5-foot Silver Bluff, recognized.

After this general survey of the Pleistocene, let us now return to the problems concerned more directly with the Pliocene-Pleistocene boundary.

PLIOCENE-PLEISTOCENE BOUNDARY IN THE GREAT PLAINS

The writers' view that the Broadwater sediments are Pleistocene rather than Pliocene is based upon several considerations:

(1) The terms "Pliocene" and "Pleistocene" inescapably imply correlation with Europe. There now can be little doubt but that the Broadwater and equivalent mammals of North America lived at essentially the same time as those mammals to which the name "Villafranchian" can be strictly applied in southern Europe (as at Perrier in part, the "Sables de Chagny", and Senèze), while the Upper Ash Hollow mammals would appear to correlate best with those of the classic Astian deposits at Montpellier in southern France and elsewhere in Europe.[6]

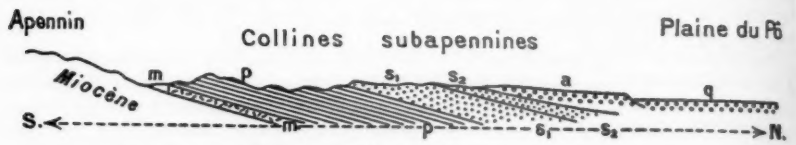
(2) Both the Pliocene and Pleistocene have definite type localities, as noted by Schenck (1935, p. 532) when he pointed out that the Miocene had a definite type locality.

Schenck quotes the passage from the preface of the third volume of Lyell's *Principles* (Lyell, 1833, pp. xii–xiii), which is also of considerable importance in the present connection:

"I had now fully decided on attempting to establish four sub-divisions of the great tertiary epoch, the same which are fully illustrated in the present work. I considered the basin of Paris and London to be the type of the first division; the beds of the Superga, of the second; the Subapennine strata of northern Italy, of the third; and Ischia and the Val di Noto, of the fourth."

[6] Osborn (1910a) and Osborn and Matthew (1909, p. 82) suggested that in a very general way the Blanco deposits of Texas (a Broadwater equivalent) would correlate with the Astian on the basis of the mammals, while Matthew (1929, p. 438–441, 530) suggested the correlation as Early Pleistocene of the Hay Springs deposits with the upper Val d'Arno deposits (the terms "upper" and "lower" have reference to geographic position) on the supposition that both represented "the outwash of early glaciation". However, J. R. Schultz (1937b) clearly pointed out the close agreement between some of the Villafranchian mammals and those from deposits here termed Broadwater equivalents, but he did not know of the mammals from Broadwater (although discovery announced in 1936) or from beds of this age in Kansas.

There is no question but that these four subdivisions are the ones named Eocene, Miocene, Older Pliocene, and Newer Pliocene by Lyell later in this same volume (Schenck, 1935, p. 532). Lyell here (1833, p. 52–55; readily available in full quotation in Wilmarth, 1925, p. 51–52) originally subdivided his Pliocene into an "Older Pliocene" and a "Newer Pliocene." The classic "Older Pliocene", based upon the formations of the Subapennine Hills or "terrain subapennin" (Gignoux



q = Alluvions *quaternaires* de la plaine du Pô.
a = Alluvions villafranchiennes..... } *Pliocène sup.*
s_2 = Sables jaunes sup. à *Cyprina islandica* (Calabrien)..... {
s_1 = — — inf. à faune astienne..... } *Pliocène inf.*
p = Marnes bleues à faune plaisancienne..... }
m = Conglomerats ou marnes lagunaires du Messinien..... *Pontien.*

— Coupe schématique du Pliocène dans la région de Plaisance (Italie).

FIGURE 3.—*Type Pliocene (Lyell's "Older Pliocene") of the Subapennine Hills in the region of Plaisance, northern Italy*

From Gignoux (1943). These type Pliocene beds are overlain by Lyell's "Newer Pliocene". The term "Pleistocene" when first proposed by Lyell in 1839 was a substitute term for the awkward "Newer Pliocene" or the Villafranchian-Calabrian sediments, while "Pliocene" was restricted to the Plaisancian-Astian and some older sediments shown here. The traditional European usage is illustrated here, but it seems to have been retained chiefly because of the "sedimentary cycle" concept of Gignoux (1913).

1943, p. 551; 1913, p. 7–8, 315) of northern Italy, is still the "Pliocène inférieur" of French and Swiss geologists (Gignoux, 1913, p. 10–11, 25, 595). At this type locality (Fig. 3), the yellow Astian sands overlie the Plaisancian (here and in southern France the Astian facies has overlapped the Plaisancian, but elsewhere they are partially contemporaneous according to Gignoux, 1913, p. 21, 315, and the earlier studies of De Stefani), and the Messinian or supposed Pontian equivalent is present at the base of the deposits.

The type locality of Lyell's "Newer Pliocene," as noted above, is on the island of Ischia and the Gulf of Naples region in central Italy. (For location see Gignoux, 1913, pl. 5 and maps in various editions of Lyell's *Principles*.) These celebrated deposits[7] consist principally of the "Marnes de l'Epomeo," which have been shown by Gignoux (1913, p. 283–284) to be without much question Calabrian (a term coined by Gignoux, 1910, for the marine facies of the Villafranchian).

The term "Pleistocene" was introduced by Lyell in 1839 (1839a, 1839b; for full quotation *see* Wilmarth, 1925, p. 47–52) as a substitute for his "Newer Pleiocene," so the type locality became the Island of Ischia and the Gulf of Naples area noted above. At this time, Lyell restricted "Pleiocene" to his "Older Pleiocene," which made the Subapennine Hills the "*type classique*" as Gignoux (1913, p. 315) expressed it.

The added definition of Pleistocene as the "glacial epoch" was by Forbes (1846; *see* quotation in Wilmarth, 1925, p. 48). Lyell (1873, p. 3–4; quoted in Wilmarth, 1925, p. 48–49) remarked that he had used the term Pleistocene in 1839 as "an abbreviation for Newer Pliocene," but that Forbes had applied the term almost precisely in the sense in which Lyell had previously used Post-Pliocene, and not as short for Newer Pliocene. Lyell then confused the matter by advising the abandonment of Pleistocene, or if its use were continued to make it synonymous with Post-Pliocene.

The European usage of these terms since 1873 has been summarized by Gignoux (1913, p. 4–11, 21–25; 1910; 1908). De Stefani, for example, used Pliocene for Lyell's "Older Pliocene," and called all later beds "Postpliocène." However, Gignoux (1913, p. 25; 1910; 1908) proposed to keep the

[7] Gignoux (1913, p. 283) states ". . . elles sont depuis longtemps célèbres, car Lyell (Eléments de Géologie, t. I[er], p. 306) les a prises pour type de son 'nouveau Pliocène'; . . . ".

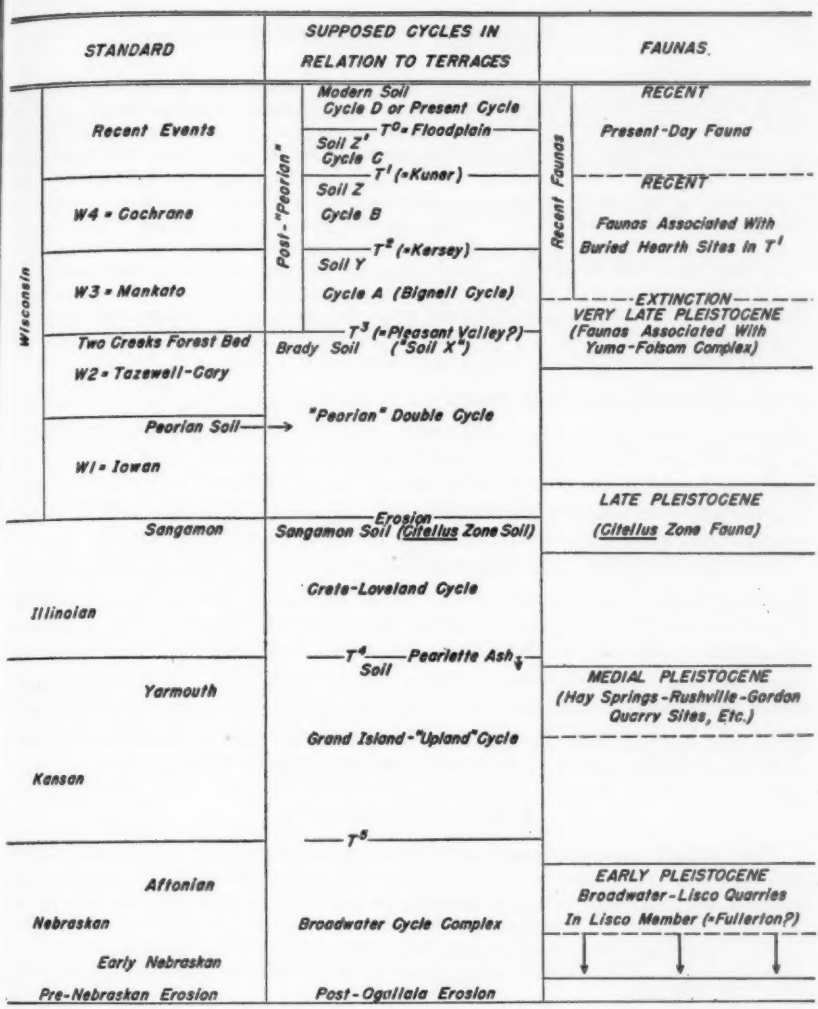


FIGURE 4.—*Suggested correlations of Pleistocene sedimentation cycles in Nebraska*

Modified slightly from Schultz and Stout (1945). The Wisconsin subdivisions and terrace names within brackets are from Bryan (1941b, p. 57) and Bryan and Ray (1940), but the numbering of the terraces on the basis of lithology and fossils as well as position has been developed by the writers and associates as a nomenclature for field study of Great Plains terraces.

The concept of the Terrace Cycle proposed by the writers (1945, Fig. 4) was an initial attempt at cyclic interpretation of these deposits, and the writers see no necessity for revision of these ideas to any extent as a result of later work. The Brady soil is proposed as a new term to replace the "Soil X" of the 1945 paper; several of the other soils and a post-Bignell loess may eventually require formal names; but this is deferred until such time as a real need for them becomes evident. It seems probable that some, if not all, of the gumbotils of the glaciated regions may be found to be represented west of the respective till borders by buried humic soils (which represent, of course, the "A" horizons of the buried soil profiles), but these relations require study by soil scientists and other specialists. The soil (or soils) at the top of the "Upland" formation is now known to occur *above* the Pearlette ash, which in turn overlies silt, sand, and the Grand Island gravel. The exact age of the Grand Island in some places cuts Kansan till and possibly even the gumbotil or soil (the Yarmouth in the original sense of the term) at the top of the Kansan till. It may be necessary to consider the upper gravel member of the Broadwater formation in western Nebraska as a Kansan gravel (since the Lisco member appears to be about a Fullerton or Aftonian equivalent). This was an interpretation suggested to the writers in 1936 by Prof. Paul MacClintock in the course of coöperative field of work in western Nebraska.

term "Older Pliocene" or "Pliocène ancien" in the original Lyellian sense for the Plaisancian and Astian (chiefly), and used the term "Newer Pliocene" or "Pliocène supérieur" in the strict sense for the Calabrian and Villafranchian, with the Quaternary beginning with the next overlying Sicilian to embrace all later beds. This usage has been generally followed by most later French and Swiss writers (Denizot, 1935), but it should be remarked that the determining factor in this has been the "sedimentary cycle" concept originated by Gignoux (1913, p. 21–25). This concept emphasized the Calabrian-Sicilian break, but the literature regarding later work seems to show that it has not been as difficult as Gignoux thought to distinguish between the Calabrian or Villafranchian and the older beds (Astian and Plaisancian). Inasmuch as the Calabrian or Villafranchian deposits are evidently type Pleistocene, and since there appears to be increasing evidence that such deposits could belong in the "Glacial Epoch," it would appear that the Pliocene could be limited to Lyell's "Older Pliocene" (as he defined it in 1839) and the Pleistocene to all later deposits without seriously modifying either the original definitions or the "Glacial Epoch" concept.

(3) If the definition of the Pleistocene as the "Glacial Epoch" be considered the all-important feature (and as noted above this is not necessarily in conflict with the original definitions), it also appears from present evidence that the Broadwater deposits and equivalents must be logically considered Pleistocene, for the Fullerton clay of eastern Nebraska (definitely Aftonian) appears to be the approximate stratigraphic correlative of the Lisco member of the Broadwater formation.

(4) The important unconformity between the Kimball and Broadwater formations is the most significant stratigraphic break in the Upper Tertiary and Pleistocene deposits of western Nebraska and of the Great Plains in general. This break was apparently produced by uplift to the west, perhaps accompanied by uplift of the High Plains (since the Ogallala is slightly folded in places). The faunal break between the Kimball and Broadwater formations is the most important one paleontologically in the Upper Tertiary and Pleistocene of western Nebraska (and Great Plains). It is the writers' opinion that this is the Pliocene-Pleistocene boundary.

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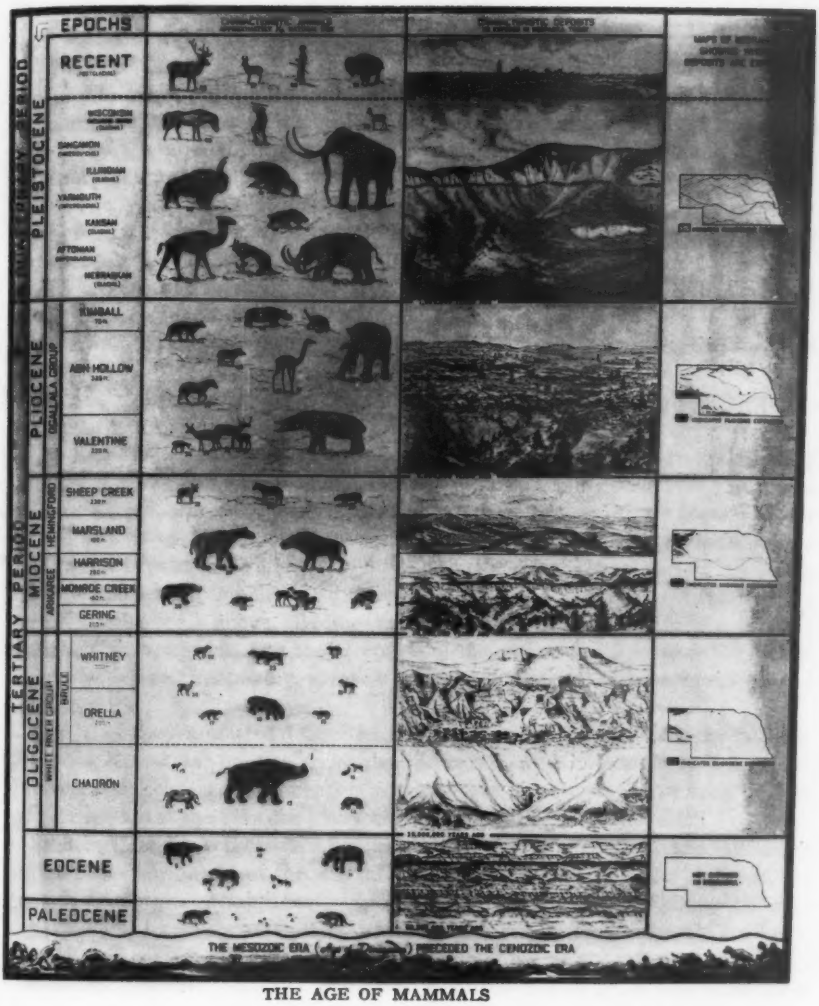
PLATE 1.—"AGE OF MAMMALS" AND A GENERALIZED CLASSIFICATION OF THE GREAT PLAINS TERTIARY AND PLEISTOCENE

Showing classification of the Great Plains Tertiary and Pleistocene, together with restorations of selected fossil mammals (and a turtle). The representative exposures shown are from Nebraska or immediately adjacent States, serving to emphasize the completeness of the Middle and Upper Tertiary as well as the Pleistocene record. It is proposed that this succession be accepted as the standard for the Continental Medial and Late Tertiary of North America. The fossil restorations shown are as follows: 1—Primitive Hoofed Mammal, *Phenacodus;* 2—Ancient Marsupial, *Peradectes;* 3—Early Primate, *Plesiadapis;* 4—Primitive Carnivore, *Claenodon;* 5—Archaic Hoofed Mammal, *Pantolambda;* 6—Titanothere, *Lambdotherium;* 7—Titanothere, *Eotitanops;* 8—*Hyracotherium* (*Eohippus*); 9—Titanothere, *Palaeosyops;* 10—Lemur, *Notharctus;* 11—Uintathere, *Uintatherium;* 12—Rhinoceros, *Trigonias;* 13—Titanothere, *Brontops,* 14—Creodont, *Hyaenodon;* 15—Deer-like Ruminant, *Pseudoprotoceras;* 16—Deer, *Leptomeryx;* 17—Saber-toothed Tiger, *Hoplophoneus;* 18—Aquatic Rhinoceros, *Metamynodon;* 19—Oreodont, *Merycoidodon;* 20—Camel, *Poebrotherium;* 21—Horse, *Mesohippus;* 22—Deer-like Ruminant, *Protoceras;* 23—Running Rhinoceros, *Hyracodon;* 24—Oreodont, *Leptauchenia;* 25—Two-horned Rhinoceros, *Diceratherium;* 26—Dog, *Mesocyon;* 27—Gazelle Camel, *Stenomylus;* 28—Oreodont, *Promerycochoerus;* 29—Moropus, *Moropus;* 30—Giant Hog, *Dinohyus;* 31—Deer-like Ruminant, *Syndyoceras;* 32—Horse, *Merychippus;* 33—Oreodont, *Brachycrus;* 34—Antelope, *Cosoryx;* 35—Three-horned Deer, *Cranioceras;* 36—Deer-like Ruminant, *Synthetoceras;* 37—Four-horned Prongbuck, *Sphenophalos;* 38—Four-tusked Mastodont, *Serridentinus;* 39—Horse, *Pliohippus;* 40—Tapir, *Tapirus;* 41—Camel, *Alticamelus;* 42—Shovel-tusked Mastodont, *Amebelodon;* 43—Dog-like Bear, *Hemicyon;* 44—Rhinoceros, *Teleoceras;* 45—Giant Tortoise, *Testudo;* 46—Giant Camel, *Gigantocamelus;* 47—Ground Sloth, *Megalonyx;* 48—Mastodont, *Stegomastodon;* 49—Saber-toothed Tiger, *Smilodon;* 50—Giant Bison, *Superbison;* 51—Giant Bear, *Arctodus;* 52—Mammoth, *Archidiskodon;* 53—Horse, *Equus;* 54—Early Man, *Homo;* 55—Four-horned Prongbuck, *Stockoceros;* 56—Wapiti or American Elk, *Cervus;* 57—Pronghorn, *Antilocapra;* 58—American Indian, *Homo;* and 59—Bison, *Bison.* Painting executed by Nathan L. Mohler, under direction of C. Bertrand Schultz.



THE AGE OF MAMMALS

INVERTEBRATES OF THE BLANCAN

BY A. B. LEONARD

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The difficulties and inadequacies inherent in attempts to use fossils as indices of stratigraphic succession in the geologic column are well known to all of us. These difficulties are especially apparent with respect to the use of molluscan faunas for this purpose for a number of reasons:

(1) The biotic requirements of mollusks are, generally speaking, relatively unrestricted, so that rather wide fluctuations in climatic conditions may occur without producing a parallel effect upon the fauna.

(2) Perhaps due to their sedentary habits, mollusks are peculiarly liable to the effects of purely local conditions.

(3) The buoyancy of gastropod shells allows for ready transportation by wind and water.

(4) Shells of terrestrial and fresh-water mollusks are peculiarly susceptible to destruction by abrasive forces, and by free acids in soil and water.

(5) Fossil shells, like gold, are where one finds them, which leads to the corollary that one is never sure when a faunal assemblage is reasonably complete. In southwestern Kansas, where my own information is most complete, we are faced with one or two serious voids in faunal succession, the Middle Pliocene Ogallala formation being a case in point. This hiatus in the known molluscan faunas bears on our immediate problem, for it impairs our attempts to interpret the relations of the Blancan faunas which appear above. Molluscan faunas from admitted Pleistocene deposits are much better known, with the exception of the gravels at the base of the Meade formation, where, presumably, abrasive forces have destroyed all usable evidence of molluscan life.

In spite of these admitted difficulties, and with the reservations inherent in them, it is possible that our present knowledge of the molluscan faunas derived from the Pliocene and Pleistocene sediments of southwestern Kansas may have some bearing on the question of the Pliocene-Pleistocene boundary in the Plains region.

Each vertical line represents a species; the vertical length of the line represents the vertical distribution of the several species as now known. The hiatus in the Ogallala is immediately apparent. Species known from the lower Pliocene Laverne formation which also appear in later deposits are shown by broken lines in the Ogallala, for they are not actually known from middle Pliocene sediments.

LAVERNE FORMATION-LOWER PLIOCENE: Eighteen species are known from these deposits, although the fauna is as yet poorly known. Of these species four, about 23 per cent, appear in later sediments, the remainder are extinct, at least in this area, and most of them are not known elsewhere at all.

SAW ROCK CANYON FAUNA: Of somewhat uncertain position in the geologic column, the Saw Rock Canyon deposits are, nevertheless, probably the oldest above the Laverne from which molluscan fauna is known. Seventeen species are known from these sediments, of which 29 per cent are restricted to the beds; about 71 per cent appear in younger deposits.

REXROAD, FOX CANYON AND BIG SPRINGS: Twenty-two species constitute the known fauna from these sediments; 45 per cent of them are restricted to these deposits, while 55 per cent of the species appear also in younger beds.

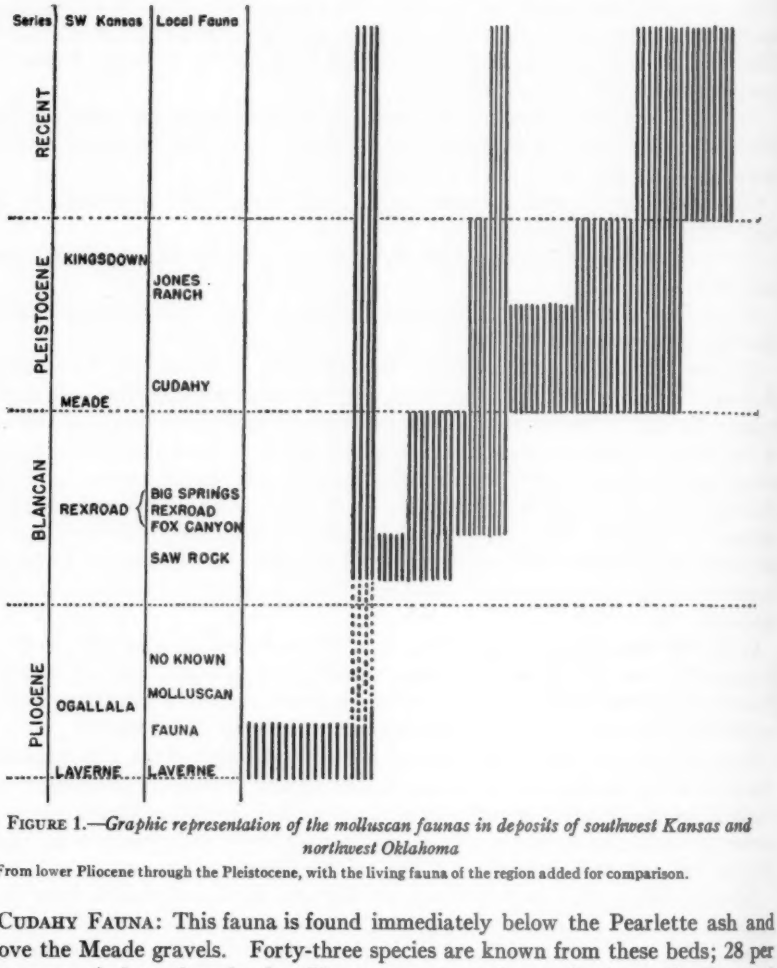

FIGURE 1.—*Graphic representation of the molluscan faunas in deposits of southwest Kansas and northwest Oklahoma*

From lower Pliocene through the Pleistocene, with the living fauna of the region added for comparison.

CUDAHY FAUNA: This fauna is found immediately below the Pearlette ash and above the Meade gravels. Forty-three species are known from these beds; 28 per cent appear in later deposits, but 72 per cent are not known in the earlier Rexroad fauna.

JONES RANCH: The Jones Ranch fauna comprises a total of 31 species as now known, of which 45 per cent do not appear in the living fauna of the region. However, the fauna differs from the older Cudahy fauna largely in that 12 species from the Cudahy do not appear in the Jones; all other species, with one possible exception not indicated on the chart, are common to the Cudahy fauna.

Another method of analysis consists of comparing adjacent faunas in the series to show the percentage of species common to both. There is an admitted error in this approach, because the absolute numbers of species in two adjacent faunas is never quite the same, which is sometimes, at least, a reflection of the thoroughness of the collection methods or the lack of it. Nevertheless, the results of such calculations are presented for whatever they may mean.

(1) The combined faunas of the Laverne and Saw Rock faunas comprises 31 species, of which 4 species are common to the two faunas—approximately 13 per cent. The character of the two faunal assemblages, however, differs more greatly than it is possible to show by figures or charts; this is no more than expected, for the time represented in the Ogallala, from which no molluscan fauna is known, is extensive, and great changes in molluscan life might be expected during this time.

(2) There are 27 species in the combined Saw Rock Canyon and Rexroad faunas, of which 45 per cent are common to both assemblages.

(3) A comparison of the Rexroad fauna with the Cudahy on the same basis results in a figure of about 23 per cent of the species appearing in common.

(4) Eighty-eight per cent of the Cudahy species are common to the Jones fauna, while

(5) Forty-two per cent of the Jones fauna is also represented in the Recent fauna of the region.

Whether one uses the figure representing the percentage of species restricted to a particular faunal assemblage, or the more vulnerable figure representing an expression of species common to two adjacent faunas, or, for that matter if one merely inspects Figure 1, it is apparent that the greatest discontinuity in the faunal assemblages occurs between the Rexroad and Cudahy deposits, if one disregards the break between the Laverne and the Saw Rock, which admittedly is a great one.

I am not prepared to draw a conclusion regarding the position of the Plio-Pleistocene boundary from these data. Until a usable molluscan fauna from the Ogallala is forthcoming, the relationships of the Blancan molluscan faunas must remain uncertain, and conclusions based on invertebrate faunal assemblages are hazardous.

LATE CENOZOIC CLIMATIC CONDITIONS IN THE HIGH PLAINS OF WESTERN KANSAS

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A consideration of the late geologic history in the High Plains region is essential to an understanding of the Cenozoic deposits in Meade and Seward counties, Kansas, and Beaver County, Oklahoma.

Prior to the deposition of the Laverne beds (Lower Pliocene) in this area the Permian beds were eroded to a considerable depth and probably collapsed, in part, to form large basins which provided traps for the majority of the Laverne deposits. After the deposition of the Laverne and apparently near the close of Hemphillian time secondary basins were developed which involved the Laverne formation (Frye, 1942, p. 23–26; Frye and Schoff, 1942, pp. 35–39). A third major development of basins occurred after the close of Meade time.[1] The development of basins and sinks in this area has been generally continuous since the close of Meade time. Many of these filled basins have been dissected by the Cimarron River and its tributaries.

The history of the deposition of the beds yielding the Blanco fauna (Rexroad) in southwestern Kansas is different from that of the deposition of the beds yielding the Blanco fauna of Texas and Nebraska. Evans and Meade (1945, p. 492) state: "The Blanco beds are believed to be lacustrine deposits laid down in broad shallow basins rather than deposits of a large stream valley, as was interpreted by Gidley (1903) and other earlier writers." In regard to the origin of the deposits in Nebraska, Schultz and Stout (1945, p. 234–235) state: "The Ogallala sediments were rather deeply eroded probably by an ancestral North Platte River, and then the alluvial deposits, which constitute the Broadwater formation were deposited. . . ." The Broadwater formation has been designated as alluvial terrace, T^6, of the North Platte River by Schultz and Stout.

The Rexroad formation (Smith, 1940, p. 95; McLaughlin, 1946, p. 33, 121) is neither lacustrine in origin nor is it a terrace deposit along the Cimarron River and its tributaries. It was laid down by a stream flowing from the Rocky Mountain region, which cut its channel into older deposits. Its course was determined, in part, by basins developed in this area. The basins trapped large amounts of sediments. The individual basins containing Rexroad sediments vary in age. The basins were developed just prior to or during Rexroad time as is shown by the sediments and fossils that they contain. This fact is revealed by the presence of the Saw Rock fauna (Hibbard, 1944a; 1944b) found at the base of the Rexroad formation in Saw Rock Canyon, Seward County, Kansas. At this locality the deposition is continuous, and it has been impossible to pick a lithologic break between the underlying beds containing the Saw Rock fauna and the overlying beds containing the Rexroad fauna. The Saw Rock fauna, consisting of *Osteoborus progressus* Hibbard, *Mammut* (*Pliomastodon*) *adamsi* Hibbard, *Baiomys*, *Perognathus*, and *Dipoides* asso-

[1] Meade time as used in this paper is restricted to that time required for the downcutting of the stream channel in which the basal Meade sands and gravels were deposited (example seen in sec. 9, T. 33 S., R. 29 W., Kansas) and the deposition of the overlying beds, the uppermost of which is the top bed in the type section of the Meade formation containing the caliche in secs. 16 and 21, T. 33 S., R. 28 W.

ciated with the abundant fragmentary remains of pond and river turtles and the numerous molluscan remains, helps to bridge the gap between the Hemphillian and Blancan faunas. New collections of the Saw Rock fauna and others of equivalent age may be expected to yield ancestral forms of the Blancan fauna.

Climatic conditions in southwest Kansas during the time of the Saw Rock fauna seem to have been comparable to conditions that existed at the time the Rexroad fauna occurred in that area. This conclusion is based on a comparison of the small Saw Rock fauna and the lithologic character of the enclosing sediments with the Blanco (Rexroad) fauna and sediments of Meade County, Kansas.

The basal Rexroad sediments are fine to coarse gray sand, lacking the coarse gravels and pebbles observed in the basal Ogallala and younger stream deposits found in the same area. From a study of the deposits constituting the Rexroad formation there appears to have been a gradual decrease in the gradient of the stream and a decrease in rainfall as the stream slowly filled its channel and flood plain with silt and clay. Near the top of the silt and clay beds are a few scattered zones showing remains of vegetation. The Rexroad fauna occurs at this level. For a discussion of the paleoecology of the Rexroad fauna *see* Hibbard (1941a), Taylor (1942), and Wetmore (1944). Above the level of the Rexroad fauna is a deposit of reddish silt grading upward into a zone of unstratified caliche from 1 to 3 feet thick. The silting up of the Rexroad stream and the development of the pronounced caliche zone within the Rexroad formation seems to indicate a shift in the climatic condition from a relatively humid climate to a semiarid one, which resulted in the formation of the caliche zone. Above the caliche zone occurs approximately 40 feet of reddish-buff sandy silt which contains some stringers of caliche. These vertical caliche stringers are secondary in origin. The silts above the main caliche zone seem to indicate a slight shift toward an increase in precipitation and runoff which resulted in the filling of the Rexroad valley. The peak of precipitation, or maximum runoff, was reached when the Meade stream cut its deep channel into the Rexroad silts and deposited the basal Meade sands and gravels. The Meade formation comprises two cycles[2] of deposition.

At the close of Rexroad time there was a rejuvenation of the stream from the Rocky Mountain region causing it to cut deeply into the underlying Rexroad deposits. It filled its channel with coarse sands and gravels. In these gravels are striated pebbles (Hibbard, 1944a, p. 742) which are interpreted as outwash from Rocky Mountain glaciers. Whether meltwater from the mountain glaciers was sufficient to cause the downcutting or whether it is correlated with an uplift in the mountain region awaits further study.

Above the basal Meade gravels are deposits of clay and reddish sandy silts which grade upward into a zone of caliche. It was from one of these silty clay deposits in sec. 15, T. 33 S., R. 29 W., Meade County, locality no. 1, just above the basal Meade sands and gravels that Hibbard (1938) recovered vertebrate remains which he confused in age with vertebrates of Rexroad age from locality no. 3, sec. 22, T. 33 S.,

[2] A cycle as used here is considered to begin with (1) the downcutting and deposition of sands and gravels, (2) the deposition of silt and clay, (3) the development of a caliche zone, and (4) the deposition of silt and clay, terminated by an increase in runoff which starts another phase of downcutting.

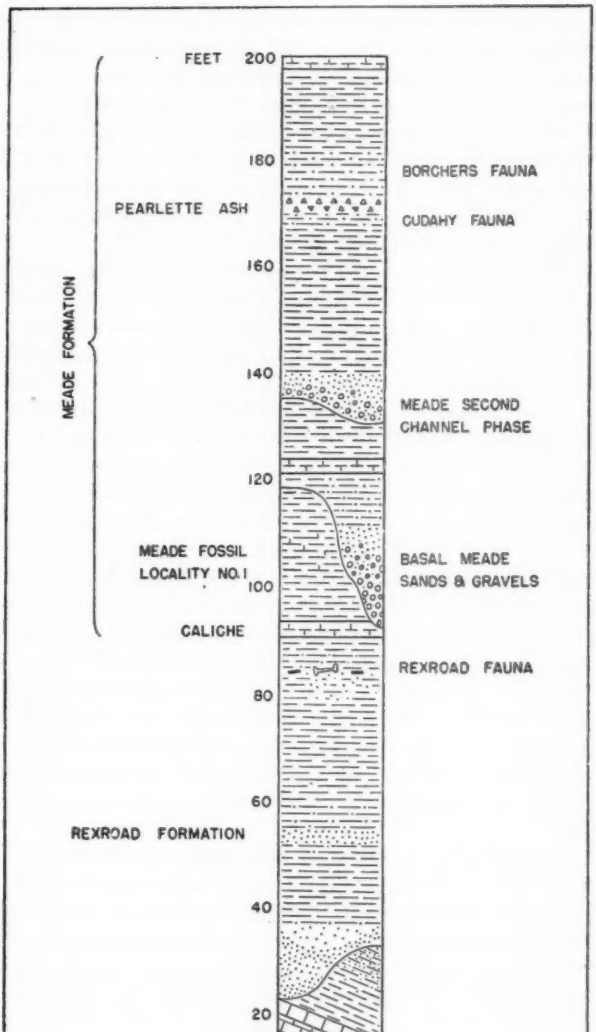

FIGURE 1.—*Diagrammatic section of late Cenozoic deposits exposed along the Cimarron River valley in Meade County, Kansas*

R. 29 W. These vertebrates, *Pliolemmus antiquus* Hibbard, *Phenacomys primaevus* Hibbard, and *Pliopotamys meadensis* Hibbard, are considered as indicating a much

cooler climate than does the Rexroad fauna. The maximum silts observed above the basal sands and gravels are approximately 20 feet thick. Most of the caliche zone and the reddish sandy silts above have been removed by the downcutting of a second channel phase. The second phase of the stream within the Meade formation channeled into the underlying beds of the Meade, but in no place is it known to have cut down to the Rexroad formation. One of the best exposures of the two sands and gravels is seen 3½ miles west of Meade, Kansas, on U. S. Highway 160, in secs. 6, 7, and 8, T. 33 S., R. 28 W. The second channel sands and gravels are well exposed at the type section of the Meade formation in sec. 21, T. 33 S., R. 28 W., on the east side of Crooked Creek where the first cycle of downcutting and deposition are missing. Clay and silts occur above the second channel sands and gravels at the type locality of the Meade formation. Interbedded in the silts and clay is the Pearlette ash member. The Cudahy fauna (Hibbard, 1944a) occurs at the base of the Pearlette ash. This fauna is believed to have lived under cool conditions. It is important to note that the Cudahy fauna, as known at present, is distinct from the faunal assemblage of locality no. 1, although they are considered to have lived under similar climatic conditions.

Just above the Pearlette ash is an extensive deposit of clay and silt. The Borchers fauna (Hibbard, 1941a) was found in these beds just above the ash. This fauna lived during an interglacial time. It shows no relationship to the Cudahy fauna but it does contain forms that occur in the Rexroad fauna.

Capping these clay and silt deposits on the east side of Crooked Creek are cobbles of caliche, and in a few places the caliche is still bedded. The caliche is better developed at this horizon on the west side of Crooked Creek and along the breaks of the Cimarron River. This extensive and massive caliche deposit is interpreted to indicate a semiarid condition for the plains region. This caliche horizon marks the top of the high plains surface in this area. Loess and dune sand cover much of the caliche. It is in this surface of deposition and distribution that the Cimarron River has cut its channel and developed its valley and terraces. The course of the Cimarron in this area is determined largely by post-Meade basins. The river has cut through the Meade and in some places through the Rexroad and Ogallala formations, leaving exposed here and there portions of the Laverne and Permian along the base of its valley walls.

The relation of the Cimarron River to the Meade formation is of great importance in the study of the Pleistocene deposits of that region. It is from deposits of post-Meade time in Meade and Seward counties, Kansas, and Beaver County, Oklahoma, that the numerous remains of *Equus* are recovered. *Plesippus* and *Nannippus* occur in the Rexroad fauna and in the two overlying Meade sands and gravels. No remains of *Bison*, *Paramylodon*, or *Mammuthus* are known from the Meade formation in these counties, but they are found in terraces along the Cimarron River or in other deposits of the same age.

The stream that deposited the sands and gravels of the Rexroad formation had a lower gradient and apparently carried a smaller quantity of water from the mountain region than the streams that deposited the Ogallala, Meade, and Cimarron River terrace sands and gravels.

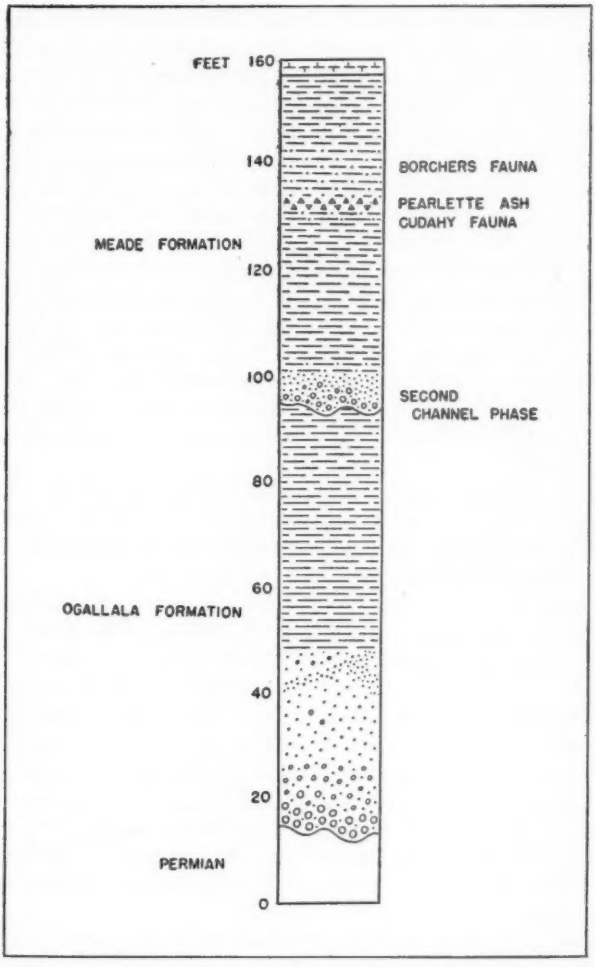

FIGURE 2.—*Diagrammatic section of deposits exposed along east side of Crooked Creek valley in Meade County, Kansas*

The type of deposition observed in the Rexroad and Meade formations seems to indicate a definite climatic cycle from a time of abundant rainfall to one of semiarid condition followed by a period of greater precipitation. The rejuvenation of the streams is probably related, in part, to uplift in the Rocky Mountain region.

There is a progressive change in faunas in this area during late Cenozoic time which appears to be correlated with climatic changes (pre-glacial, glacial, and interglacial ages).

The mammalian genera of the Blancan fauna are of longer range and are not re-

stricted to the Blancan as considered by many geologists. A majority of the genera range through Hemphillian, post-Hemphillian—pre-Blancan and post-Blancan time as revealed by the Edson Quarry fauna, the Saw Rock fauna, and the vertebrate remains from the Meade formation.

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PLIOCENE-PLEISTOCENE BOUNDARY IN THE GREAT PLAINS—EVIDENCE AND PROBLEMS

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In the central and southern Great Plains region late Tertiary deposits accumulated first in the area where Colorado, Wyoming, and Nebraska meet; during Pliocene time they spread southward over the region of western Nebraska, Kansas, Oklahoma, and Texas and eastern Colorado and New Mexico. These Pliocene strata represent stream deposits of coarse to fine clastic material and over most of the region are largely classed as the Ogallala formation. The depositing streams of the Ogallala flowing east and southeast from the Rocky Mountain region, spread a sheet of sediment over an erosion surface of low relief, filled the shallow pre-Pliocene valleys, and built the surface of an extensive alluvial plain well above the highest points on the earlier interstream divides. By the end of Ogallala deposition a graded alluvial plain extended in Kansas from near the Flint Hills westward to the Rocky Mountain region, and there merged with the erosion surface in the mountains. This surface may have remained for an undetermined length of time in a state of equilibrium while the so-called Algal limestone was formed in consequent depressions and abandoned channel lakes (Frye, 1945b). Later the streams started to erode and develop valleys below the upper surface of the Ogallala. The history of the Great Plains during subsequent time was characterized by alternate periods of erosion and of deposition, modified at times by widespread eolian activity, stream piracies, faults in a few areas, and the development of solution-subsidence basins. Sometime after the close of Ogallala deposition the geologic epoch called Pliocene ended, and that called Pleistocene began.

Pleistocene is recognized almost universally by geologists as a valid and important interval of geologic time, characterized in high latitudes and altitudes by repeated glaciation and over much wider areas by repeated fluctuations of climate. However, definitions and usages that have served to set off the beginning of this time interval within the areas directly affected by continental glaciation fail to establish it clearly within the succession of sediments and erosion intervals that have been studied in the Great Plains. Although boundaries used in classification of marine strata have not been clearly correlated with those used in the glaciated areas, Pleistocene is presumed to include the time of glaciation generally throughout the world. The coincidence of the Tertiary-Quaternary systemic boundary line with this series boundary presumably emphasizes its importance but furnishes us with no additional criteria for its recognition. The late Cenozoic chronology generally used in the Great Plains is based largely on land vertebrates that, for the most part, have not been found in association with either fossiliferous marine strata or a correlatable sequence of glacial deposits. Thus the late Cenozoic time terms as used in this area may not be synchronous with the same terms when used to include marine or glacial sediments.

Our problem is then to examine the basis of Pleistocene time classification and to find some means by which we can correlate events in the plains with events that elsewhere may be considered as marking the beginning of the Pleistocene.

Let us first examine the possibility of establishing a boundary line based on tectonic events. For example, data have been presented recently (Pilgrim, 1944) for placing the beginning of Pleistocene in both India and China at a time of pronounced tectonic activity. Likewise it has been argued that terraces thought to be Pliocene in age along the Atlantic coast of North America were tilted prior to the development of essentially horizontal terraces of supposed Pleistocene age (Cooke, 1930, p. 589), and that pronounced uplift occurred in the Rocky Mountain region at the beginning of Quaternary (Blackwelder, 1915, p. 210). Uplifts or tectonic movements of uncertain character have been postulated in other areas, and it has been reasoned that continental glaciation was initiated by elevation of mountain belts. Furthermore, diastrophism may have produced climatic changes, considered by Schultz (1938, p. 96) as the prime cause of change in vertebrate faunal assemblages. On the other hand, some geologists (Berry, 1929) hold that diastrophic events do not afford basis for time-unit classification because there is proof neither of their periodicity nor world-wide synchroniety. It is thought (Eaton, 1928, p. 114; Reed and Hollister, 1936, p. 1595) that pronounced diastrophism did not mark the beginning of the Pleistocene in California, and Schuchert and Dunbar (1941, p. 142) in their recent textbook state: "In every respect the Pleistocene epoch is allied with the Pliocene, and if it were not for the extensive glaciation that characterized the Pleistocene, the two would probably never have been differentiated."

Now we may ask, "Is it possible to find in the Great Plains evidences of diastrophism that might serve to mark the beginning of Pleistocene?" In this region the most profound change in physical conditions occurred at the culmination of Ogallala deposition when regional upward accumulation of clastic sediments gave place to intermittent erosion and deposition in local areas, which developed a thick section of sediments only locally where trapped in downfaulted or solution-subsidence areas. The oldest post-Ogallala sediments in this region (Fig. 1) have generally been correlated by their contained vertebrate faunas with the Blanco formation of Texas (McGrew, 1944), and owing to uncertainty in proper placement of these faunas in the standard time classification it has recently been suggested (Elias, *et al.*, 1945) that such placement be held in abeyance until more conclusive data are obtained. In Nebraska (Schultz and Stout, 1945) deposits of Blancan age have been described as terraces formed in a shallow valley cut below the upper surface of the Ogallala, and in Texas (Evans and Meade, 1945) the Blanco beds also are found below the general upland surface of the Ogallala and were deposited in either a stream valley or a relatively large basin. In both these areas the evidence seems clear that the general upward accumulation of stream sediments proceeding throughout much of Pliocene time was interrupted by erosion. This change may have been occasioned by regional uplift or climatic change. Initially, post-Ogallala sedimentation was restricted to small isolated areas but later became widespread throughout the plains in major valleys and depressions produced both by faulting and solution-subsidence. In Kansas the data concerning the relationship of beds of Blancan age—definitely recognized only in the area of the Meade basin—are somewhat conflicting, probably because of complications in this area by faults that cut both Pliocene and Pleistocene strata and numerous filled solution-subsidence basins. One interpretation (Frye

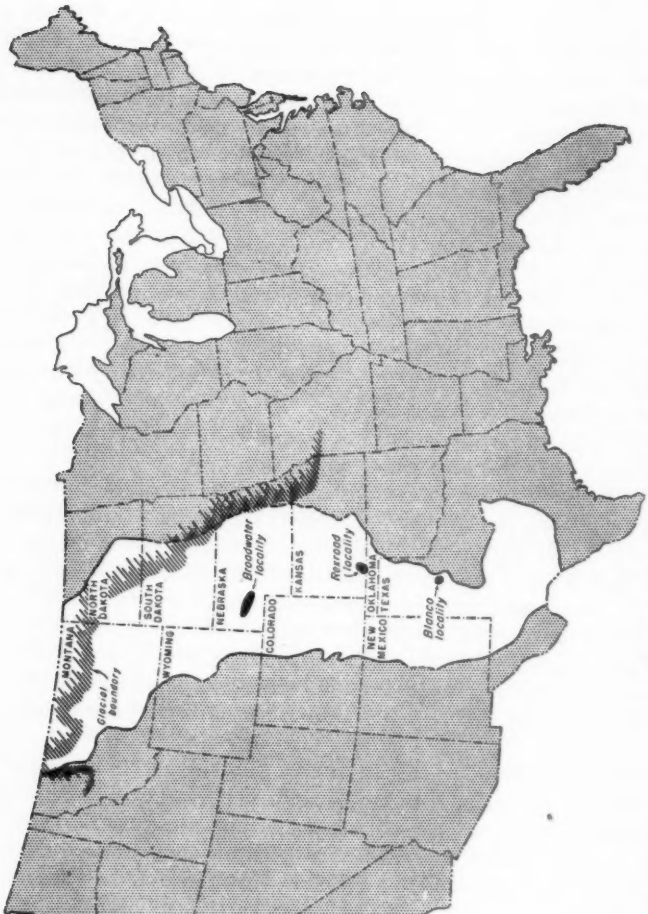


FIGURE 1.—*Map of the United States*

Showing location of the Great Plains (after Fenneman, 1931), glacial border in the Plains (after Flint, 1945), and the Blancan localities discussed.

and Hibbard, 1941) is that sediments of this age were trapped to the west and on the downthrown side of a fault which may have been active during Blancan time and that a relatively thick section of these deposits accumulated with seeming conformability above strata correlated with the Ogallala formation of other parts of the High Plains region. Such a history, controlled by local structural conditions, seems to shed little light on the immediate problem under consideration. Recently (McLaughlin, 1946) it has been argued that, after the completion of regional Ogallala deposition and before the accumulation of Blancan sediments, erosion removed the Ogallala from a very large area, including not only parts of the Meade basin lying on the downthrown side of the major fault—although not removing it from the upthrown side—but from a region extending 80 miles east-west and at least 60 miles north-south. This interpretation correlates with the Blancan this vast area of sediment that had been generally considered properly classed as Ogallala and, if accepted, furnishes us with a much greater hiatus between Blancan and older deposits than had been suspected from other regions.

Thus, in pursuing the diastrophic approach to geologic time classification, the available data from the Great Plains seem to indicate that the most profound change since the initiation of Pliocene sedimentation is marked by the cessation of deposition at the top of the Ogallala and the following interval of erosion.

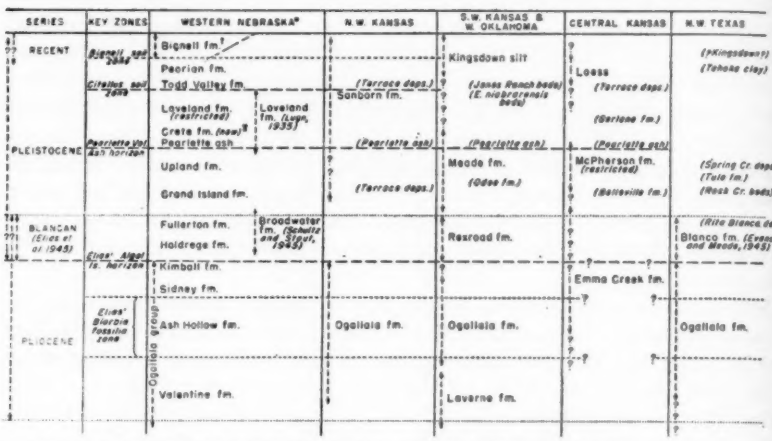
The second possible approach to the determination of the beginning of the Pleistocene in the Great Plains is that of correlation of the strata with those of other areas where this time line is more securely established.

Fossil vertebrates have been used successfully for correlations within the region, but the available faunal data do not yet seem adequate to make firm correlation with either the marine or glacial section.

Other methods of correlation are (1) stratigraphic continuity, (2) lithologic similarities, or (3) physiographic means such as tracing terrace levels from the plains eastward into the glaciated area and there relating them to the succession of glacial deposits. Such correlation may provide uniformity of classification in the several areas. The area that seems to be best suited to such studies is Nebraska and Kansas where glacial and nonglacial deposits occur in relatively close proximity.

(1) The very nature of the Great Plains deposits, in which individual beds are commonly lenticular and discontinuous, makes the task of tracing thin stratigraphic units over wide areas virtually impossible. This task is further complicated by the diversity of stratigraphic names in current use for the Pleistocene deposits throughout the plains (Fig. 2), each unit having its special local significance and none of them being now considered an exact age equivalent of any other. Beds of Blancan age are called Blanco in Texas (Evans and Meade, 1945), Rexroad in Kansas (Smith, 1940), and Broadwater, which may be equivalent to Holdrege and Fullerton, in Nebraska (McGrew, 1944, p. 35; Schultz and Stout, 1945; E. C. Reed, personal communication). In southwestern Kansas and adjacent Oklahoma the Meade formation overlies Rexroad and is overlain by Kingsdown silt (Frye, 1946), which closely resembles the unnamed Pleistocene or Recent upland silt and sand of northwestern Texas and adjacent New Mexico. The McPherson formation of central Kansas has been correlated with some beds of the Meade formation. In northwestern Kansas

virtually the entire Pleistocene section has been placed in the Sanborn formation which may be correlatable in part with the Meade and Kingsdown (Frye, 1945a) but is thought to contain no Blanco equivalent. In Nebraska (Lugn, 1935; Schultz and Stout, 1945; E. C. Reed, personal communication) the nonglacial deposits have been



* Present classification of Nebraska Geological Survey (Personal communication, E.C. Reed, Nov.18 and Dec.4, 1946).
† Separable from Peorian Complex only locally (Schultz and Stout, 1945).
‡ Condra, G.E., and Reed, E.C., in press.

FIGURE 2.—*Tentative correlation of High Plains Pliocene-Pleistocene formations*

grouped into the Platte series including the Holdrege, Fullerton, Grand Island, and Upland formations, and the Plains series including the Loveland with the Pearlette volcanic ash at the base, Todd Valley, Peorian, and Bignell formations and Recent alluvium and loess. The Plains series, exclusive of the Recent alluvium, is included within the time span of the Sanborn formation of northern Kansas, and this formation may also contain some beds correlatable with formations of the Platte series.

(2) The use of unique or distinctive lithologies as stratigraphic markers holds promise for detailed correlation. Recent studies have shown the stratigraphic value of petrographic studies of the lenticular beds of volcanic ash (Swineford and Frye, 1946) that occur in association with Hibbard's Cudahy faunal zone, but such work has not yet been carried into the glaciated area. In Nebraska glacial and nonglacial sediments are associated over a relatively wide area, and study of well cuttings from there may yield significant data. Heavy-mineral studies as a technique of detailed correlation have not as yet been carried on in this region.

(3) Terraces of the Kansas River system offer a possible means of correlation as the headwater tributaries of this system start on the west side of the High Plains section, and terraces may be traceable eastward into the glaciated area.

To date none of these several methods of approach has been carried far enough to assure successful correlations.

In summary, there exists in the Great Plains region a widespread sheet of terrestrial

deposits, now classed as the Pliocene Ogallala formation, formed by upward accumulation of fluviatile sediments. It is thought that at the close of Ogallala deposition a graded alluvial plain extended more than 1000 miles north-south and several hundred miles east from the Rocky Mountain region. Subsequently this surface was lowered locally by solution-subsidence and faulting, and over much of the region was trenched by streams. Valleys cut below the Ogallala plain later were alluviated, as were solution-subsidence basins and downfaulted areas. Alternate intervals of erosion and sedimentation since the initial dissection of the Ogallala have given rise to widespread deposits now included within a sizable number of named formations. The problem under consideration is the placement, within this sequence of events, of a line marking the end of geologic time called Pliocene and the beginning of that called Pleistocene. Seemingly the most important first step toward lasting solution of this problem is definition of terms and agreement on principles. What are the essential criteria for recognition of the Pliocene-Pleistocene boundary? Should this line be based on diastrophism? Can it be defined in terms of climatic change? Is it to be expressed by progressive change in vertebrate or invertebrate faunas? Can we countenance an essentially arbitrary method of classification and start Pleistocene time with the appearance, near its maximum limit, of the first known continental glacier? Or, ignoring these things, do precedents in geology dictate that we accept type localities based on marine beds as basis of classification, remembering, if we do so, that Pliocene and Pleistocene were both first used to include marine strata at different localities, and attempt to correlate throughout the world the time interval thus established?

Agreement concerning the basis of Pleistocene time classification will not yet answer the question of the boundary in the Great Plains. If diastrophic events or climatic change are acceptable criteria, we must determine which of the post-Ogallala erosion intervals should be chosen. If pronounced faunal changes are utilized, we must strive to correlate such a line with other regions lacking such faunal assemblages. On the other hand, if we accept the base of the Nebraskan till in the Missouri Valley as marking the beginning of the Pleistocene, the available data should be re-examined with respect to the placement of the Blancan. Furthermore, we must decide if such a line is meaningful in a succession of vertebrate faunas when it seems most likely that climatic change—the prime mover of land vertebrates—preceded considerably the appearance of the Nebraskan ice in northeastern Kansas. The following discussions should bring us closer to answers for these questions in addition to presenting specific data from various areas throughout the plains.

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TERTIARY-PLEISTOCENE TRANSITION AT THE EAST MARGIN OF THE ROCKY MOUNTAINS

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INTRODUCTION

Our study of the physiographic history of the Rocky Mountain area has aroused in us a keen interest in the relationship of our region of study to that of the Great Plains province. These adjoining areas were both high above sea level during late geologic time, and we recognize that the great physical events that punctuate earth history in this portion of the continent must be recorded in each of these physiographic provinces. The interpretation of that record is the challenge we should meet.

LATE TERTIARY LANDSCAPE IN THE ROCKY MOUNTAINS

Above the widespread Rocky Mountain peneplain, which was probably completed in early or mid-Pliocene time, there remained several areas with bold and picturesque relief. The San Juan Mountains were not completely subdued. In the Needle Mountain area of that range, conspicuous monadnock forms rise above the subsummit peneplain. In Colorado, Pike's Peak, Long's Peak, Mt. Evans, and all the beautiful crest-line features in Rocky Mountain National Park were monadnocks. In the Sawatch Range there were magnificent monadnock peaks. The crest-line features of the Wind River, Gore, Mosquito, Sangre de Cristo, and Bighorn ranges are all monadnocks of this age, and they continue to the present day to rise above the great, widespread Rocky Mountain peneplain. The Snowy Range in the midst of the Medicine Bow Mountain area rises distinctly above the peneplain surface.

The alluviation, which was proceeding as the Rocky Mountain peneplain developed, resulted in the accumulation of sediments in the Wyoming Basin, South Park, North Park, the Bighorn Basin, the Uinta Basin, and east of the Rocky Mountains in the area of the Great Plains. Some mountainous areas were actually buried beneath these slowly accumulating sediments. Other mountain areas were partially buried. Thus, in the Wyoming Basin, in North Park, and in the Bighorn Basin, the complex mountain structures that are beginning to appear again today were completely masked by alluvial deposits before the close of the mid-Tertiary period of filling. Most of the Granite Range of central Wyoming was buried. The northwest end of the Wind River Range and probably all of the Gros Ventre Range were mantled. Similar deposits must have covered parts of the Laramie and Medicine Bow ranges. During this same period, mid-Tertiary vulcanism buried various portions of the Rocky Mountain area.

The long period of erosion and basin filling produced a monotonous old-age landscape. The mountain areas, although possessing some rugged features, were, in large part, subdued to the peneplain stage. The intermontane basins were nearly or completely filled with sediments which in places actually mantled the peneplaned portions of the mountain ranges.

HIGH-LEVEL BOULDER CONGLOMERATES

Near the close of the long period of mountain denudation and basin filling, a vast amount of gravel and boulders was spread out about the margins of many of the ranges. They now cap outlying mesas in the Wyoming Basin; they rest high on the slopes of the Bighorn Range and are particularly widespread on both the north and the south slopes of the Uinta Range.

Clarence King (1871), in his studies near the 40th Parallel, mapped and described large areas capped with what he called the Wyoming conglomerate. Later observers have adopted the name Bishop conglomerate for this same formation. Near the Uinta Range it contains well-rounded quartzite boulders, 3 to 4 feet in diameter. Farther from the mountains the material grades into cobblestones and, at distances of 20 to 30 miles from the mountains, to fine gravel. The Bishop conglomerate is evidently a stream wash made up of numerous alluvial fans which are more or less blended on the pediments and in the relatively flat lands that border the present Uinta Mountains.

There are extensive areas about the margins of the San Juan Mountains that are capped with a bouldery formation similar to the Bishop conglomerate and of about the same age. In southwestern Colorado the mantle of wash material from the mountains has been traced outward for 50 miles from the base of the San Juan Range. Remnants of that coarse conglomerate remain on Bridge Timber Mountain and on the Mesa Verde, which have been separated from the mountain area by subsequent valley cutting.

We believe the Arikaree and Ogallala formations, which mantle the High Plains east of the Rocky Mountains, represent a late stage in this period of alluviation and basin filling.

From the physiographer's point of view, the Bishop and similar conglomerates suggest more than the closing of a long period of alluviation and sedimentation. They may mean the rejuvenation of streams in their headwaters, and thus mark the beginning of a new cycle of erosion in the neighboring highlands. The suggestion has been made by Bradley (1936) that they may record an increase in aridity.

A WIDESPREAD UPLIFT

Late in Tertiary time, after the mountain ranges had been subdued, after thousands of feet of mid-Tertiary sediments had accumulated, after the great volcanic flows of Colorado, Wyoming, and Idaho had poured forth, after the vast quantities of ejectamenta had settled and accumulated as breccias, tuffs, and ash beds, and just before the opening of the Pleistocene period, there occurred throughout the Rocky Mountain region another physical revolution of major significance. The movement this time was widespread; it was epirogenic rather than orogenic. The mountain ranges were somewhat emphasized, but the most significant feature was the widespread general uplift. We believe that the entire Rocky Mountain region was affected and that the neighboring physiographic provinces, including the Great Plains to the east and the High Plateaus to the west, were raised. Probably the entire Cordilleran section of North America was involved in the movement.

CANYON CUTTING

Accompanying the uplift there was a gradual quickening of streams. Thousands, perhaps millions, of years passed before the rejuvenated Colorado River, working headward through the great plateau section, cut the Grand Canyon in Arizona and finally affected the work of its tributaries in the southwestern portion of the mountain province. An equally long period passed before the quickening of the Arkansas, South Platte, North Platte, Laramie, Sweetwater, Missouri, Yellowstone, and Snake rivers affected the development of valleys within the Rocky Mountain province.

When the quickening influence finally reached the mountain area, the old-age rivers of the previous cycle took on the characteristics of youth and began to lower their courses. They cut through the mid-Tertiary alluvium to encounter hard rocks, for virtually all the streams were flowing, at places, over buried mountain ranges. Those streams which were located on bare peneplaned surfaces experienced similar difficulties. They all found it necessary to attack the ancient rock formations and in nearly every instance they cut magnificent water gaps which, today, are among the most striking physiographic features in the mountain area.

There is not a single major river leaving the Rocky Mountain region today that does not plunge through a mountain range. Several of the master streams have cut canyons in two or more ranges. There are at least 25 notable water gaps in the middle and southern portions of the Rocky Mountains within the United States. Most of these are true examples of superposition, where the streams have cut through a mantle that buried the underlying mountain structures.

OPENING OF THE LAST GREAT ICE AGE

Morainic deposits that mark the opening of the last great ice age in the Rocky Mountain province have been found at 18 different and widely separated localities. They contain at certain localities boulders of middle or late Tertiary lavas. They were not laid down until after a Pliocene peneplain in the mountain province was uplifted and somewhat dissected. Although at the surface at all known localities, they are much older than the conspicuous deposits left by alpine glaciers of two later stages and reported as present in nearly every range in the Rocky Mountains of the United States and Canada.

These early morainic deposits are located on high ridges between modern stream valleys cut a little below the Rocky Mountain peneplain horizon. They are definitely not related to the modern glaciated canyons and they are far beyond the points reached by late Pleistocene ice.

The distribution and topographic relations of the glacial deposits referred to indicate that the early ice formed in high mountains. It was after the uplift which raised and deformed the late Tertiary cycle-end-surface that snows accumulated and these early glaciers came into existence. Some of the new-cycle dissection had taken place before the ice descended from the mountains. The distribution and topographic relations of these deposits of drift indicate, furthermore, that there has been a renewal of mountain growth during the Pleistocene, which accounts for a later rejuvenation of streams, a great deepening of valleys, the excavation of huge can-

yons, the removal of vast quantities of alluvial material from intermontane basins, the resurrection of certain mountains that were buried during mid-Tertiary time, and the re-emphasis of the crest-line peaks of the larger mountain ranges. All this occurred since the early moraines were deposited. In view of the great antiquity of these glacial formations they have been correlated tentatively with the oldest moraines recognized in the upper Mississippi valley.

LAST STAGES IN EROSION

Since the widespread uplift in late Tertiary time which rejuvenated all streams in the Rocky Mountains, there have been several subsequent, though minor, uplifts. Each of these has affected the work of streams and caused variety in the topographic features that developed as the peneplain areas were dissected.

The streams widened their valleys, producing broad, parklike areas at many places. These broadened valleys and parks are higher than the modern canyons. They represent the valley-and-park stage in which the broad, open, outer valleys, now high above the modern canyons, were developed.

Then came a distinct canyon-cutting period when the present valleys were excavated. In several canyons there are spurs and benches, and it appears in many cases that the canyon-cutting stage should be subdivided into at least two parts. These should be recognized in the Great Plains.

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OGALLALA AND POST-OGALLALA SEDIMENTS

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PREAMBLE

The difficult problem of the boundary between Pliocene and Pleistocene can be helped considerably through an advanced knowledge of our Pliocene. Because the most extensive and best-known sediments of this age in America are represented by the Ogallala, the relationship of this series to post-Ogallala sediments will be largely considered in the following discussion.

NATURE AND SIGNIFICANCE OF THE OGALLALA

If we are not unduly anthropocentric in rating Quaternary a period of time aside from Tertiary, and thus are justified in looking for a major diastrophism as a natural boundary between the two—then we can hardly make any choice other than to accept the end of Ogallala time as the natural end of Pliocene time and the beginning of Pleistocene, as the period of time that, geologically speaking, has just begun.

The considerable consolidation, mostly through calcareous cementation, of the bulk of the Ogallala, its wide extent and comparatively common exposures, and characteristic fossilized seeds of grasses and borages make the formation readily identifiable in most areas of its occurrence, both on the surface and in the ordinary cut samples from the drilled wells. The fossil herbaceous seeds provided a means for zoning of all thickness of the Ogallala (Elias, 1942), except its uppermost part, which is devoid of seeds and other identifiable fossils. It is marked, on the other hand, by peculiar lithology of the cap rock and, in addition, by some locally developed quartzitic and moss-agate beds below it. Because of the zoning of the Ogallala, thus accomplished, it is possible to establish the eastward overlap of the Ogallala over the erosional surface of the underlying older formations, and also to estimate the amount of erosion suffered by the Ogallala in Pleistocene time. The cap rock of the Ogallala is a veritable datum or key bed, and, as it originated at the end of Ogallala time, it is particularly important to know it and to try to understand its origin.

CAP ROCKS

The final deposits in each of the major cycles of late Tertiary time in the High Plains are marked by concentration of calcium carbonate, which results in formation of resistant cap rock. The cap-rock of the Ogallala is by far the most extensive and best known. It furnishes the conspicuous rim rock that produces the bold escarpment around the Llano Estacado or the southern end of the High Plains. Toward the north this cap rock becomes generally less conspicuous. Its disconnected and, at most places, rather thin remnants lap over the conspicuous benches of underlying resistant Cretaceous rocks: Dakota sandstone, Greenhorn limestone, and Fort Hays limestone. Near the Nebraska line the cap rock disappears except in the northwestern corner of Kansas, where it extends over northeastern Colorado and enters into the pan handle of Nebraska near Kimball and Sidney. Disappearance of the cap

rock in the north resulted in the disappearance of the sharp physiographic boundary of the High Plains in the northeast. This boundary is barely recognizable in south-central Nebraska, and toward the north it can be drawn only arbitrarily, as it is physiographically overwhelmed by huge geological blowouts of the Ogallala, known as the Sand Hills. If the cap rock existed over this area no such extensive blowouts could possibly have been formed.

DIFFERENTIATION OF POST-OGALLALA FROM OGALLALA DEPOSITS

The Ogallala sands that are unprotected by cap rock and poorly consolidated provide readily available material for erosion and redeposition, and this fact accounts for local difficulties in differentiation between the Ogallala and post-Ogallala deposits. The general impression of lithologic similarity of the Ogallala and some post-Ogallala formations, such as the Rexroad in Kansas, is due to this fact, and in the Rexroad, as well as in other post-Ogallala deposits, the most characteristic feature is the presence in some beds of lithologic features unknown in the Ogallala. Typical, for instance, is the presence of gray silts and clays, even though they are few, while the mass of deposition consists of pinkish arenaceous material derived and redeposited from the near-by Ogallala. Northeast of Nebraska and farther north and east the Ogallala generally loses its predominant pinkish coloration, so typical of it in the west and south, and is frequently greenish to light gray. The most reliable features by which it is usually differentiated from the overlying Pleistocene are presence of (1) some cementing lime, which produces cavernous lumps, and (2) silicified seeds of prairie grasses and borages, which are unknown in the Pleistocene, except through redeposition from the Ogallala. On the other hand, positive indications of post-Ogallala deposition are the presence of (1) unctuous clays and (2) shells of snails and clams. These are practically unknown in the Ogallala as shells, but snails are not uncommon in it in the form of external molds in some white marls. The presence of the Ogallala in the area west of St. Louis, Missouri, is indicated by fossilized seeds of two borages: *Biorbia fossilia* (Berry) and *Krynitzkia coroniformis* Elias, which were found redeposited in the loess west of the city. Probably they were derived from the local gravels and sands, which are usually referred to Pliocene.

In the northeastern area of the Great Plains the division between Pliocene and Pleistocene is particularly difficult to recognize, because lithologic and paleontologic differences between corresponding formations are inconspicuous, and no momentous physiographic and erosional events marking the end of Tertiary can be easily recognized. The late Tertiary rocks are poorly represented. Thus, understanding and recognition of the Pliocene-Pleistocene boundary in this northeastern region of the Great Plains can be facilitated through better understanding of the events at the closing of Tertiary time, as manifested more conspicuously and clearly in the region of the High Plains. Here the cap rock of the Ogallala provides a prominent and easily recognizable geologic and physiographic datum, which bears the marks of momentous events at the closing of the Tertiary and initiation of Quaternary time.

SIGNIFICANCE OF CAP ROCK IN THE OGALLALA

Understanding of the origin of the cap rock of the Ogallala has been somewhat retarded by attempts to explain it as just another case of secondary concentration

and hardening of lime, which is so common at or near the surface in all permeable formations in the semiarid and arid west. The term caliche, introduced in geologic terminology from Spanish-speaking countries, became widely and unreservedly applied to terrestrial concentrations of lime, and the cap rock of the Ogallala was also labeled so. Soil scientists extended the term caliche to include lime concentration in soil profiles of pedocals that constitute a great group of the soils of western America. However, through recent detailed study of lithology, distribution, and stratigraphic relationships of the cap rock of the Ogallala, it has been reasonably proved that it is not secondarily enriched with lime but is an originally deposited calcareous rock formation that belongs in the final phase of the cycle of deposition of Ogallala time. At the very top of the cap rock is a layer of pisolitic, dense, usually pinkish limestone, whose general appearance, structural relationships to the other constituents of the cap rock, and microstructure indicate that in its origin some simple, minute, colonial algae played an important part (Elias, 1931). It resembles closely some of the limestones in the Green River Tertiary, in which minute algae also contributed to lime precipitation (Bradley, 1929). In a few cases oölites were also encountered (Frye, 1945) together with pisolitic limestone of the cap rock (Price *et al.*, 1946). Characteristic structure and extensive areal distribution of the pisolitic algal limestone in the cap rock are similar to those of the algal limestone now being deposited along the shores of the Great Salt Lake and suggest that, at the end of Ogallala time, the area of the High Plains was covered by shallow lakes, along the shores of which similar minute colonial algae took part in precipitation of calcium carbonate. The same kind of oölite, that has been found with the pisolitic limestone of the Ogallala, has been found also along the shores of Great Salt Lake and is known to be precipitated chemically.

POST-OGALLALA SEDIMENTS IN THE HIGH PLAINS

Subsequent to the deposition of the cap rock, the Ogallala, as well as the older formations in the Piedmont of the Rocky Mountains, was eroded; this erosion has continued to the present. However, some local post-Ogallala deposition has taken place at isolated sites and at various times since the closing of Ogallala time, and the oldest of these, known as Blancan deposits, are still under dispute as to their classification as Pliocene or Pleistocene (Elias *et al.*, 1945). They are located higher than any other post-Ogallala deposits (except wind-blown sand dunes and loess), have some lithologic similarity to Ogallala rocks, and contain rich faunas, which some paleontologists consider to have stronger affinities with Pliocene than with Pleistocene mammals. One time they were classified even with the Miocene. In the south these deposits also have a calcareous cap rock, with some pisolitic limestone at its top, but this cap rock is much thinner than that at the top of the Ogallala; it is also distinguished by abundance of quartzitic pebbles in its pisolitic limestone. That which caps the Gatuña (early Pleistocene) formation of New Mexico seems of Blancan age. The deposits of Blancan age are very localized and far apart. In Texas, New Mexico (probably), Kansas, and Nebraska, the sediments are unique and differ from each other both in lithologic characteristics and geological aspects. In Texas they are largely white marl with some sands below, which is believed to be a valley fill by some, but recently it has been concluded that it was deposited in a lake.

In Kansas they are lithologically similar to silty sands of the Ogallala and fill the huge sink-holes of Meade County. In Nebraska they make a distinct terrace and are made up of greenish sand with some diatomaceous marl. In New Mexico, if Gatuña is correlated with them (*compare* De Ford, 1942), they are largely sand and gravel with pisolitic limestone cap at the top. Everywhere these deposits are the topographically highest among all local post-Ogallala sediments, and their highest beds may reach locally almost as high as the cap rock of the Ogallala.

The following distinctive features seem to indicate that the Blancan is a post-Ogallala deposit and that Blancan deposits should be added rather to Quaternary than to Pliocene deposits of the High Plains:

(1) Deposition of Blancan time is very localized in distribution.
(2) The abundant seeds of prairie grasses and borages disappear at or near the base of the cap rock of the Ogallala and have never been found in the deposits of Blancan time.
(3) A pronounced erosional unconformity separates them from the Ogallala.
(4) Typically, the deposits of Blancan age cannot be said to overlie the Ogallala, but rather lean against it, as they occupy a slightly lower position.

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STRATIGRAPHY AND GEOMORPHOLOGY OF THE PLEISTOCENE OF NEBRASKA

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This report represents the current understanding of the Nebraska Geological Survey regarding the Pleistocene of Nebraska and is based on recent studies of surface exposures supplemented by subsurface studies made in connection with ground-water investigations. The data on which the current conclusions are based will be published at an early date as a bulletin of the Nebraska Geological Survey entitled *The correlation of the Pleistocene formations of Nebraska* by G. E. Condra and the speaker.

Nebraska is in a strategic position for Pleistocene studies because the eastern fourth of the State was traversed by the Nebraskan and Kansan continental glaciers, and extensive attendant deposits occur over much of the rest of the State. Thus it is possible, through close surface and subsurface studies, to work out the relationships between the Nebraskan and Kansan tills and the correlative deposits west of the till borders and to establish a firm basis for the correlation of the post-Kansan Pleistocene with the later glaciations which did not reach the area but which did leave a strong imprint on the record.

Controlled test drilling with State-owned and operated drilling equipment along scientifically designed profiles at strategic intervals, augmented by laboratory study of samples, has removed much interpretive speculation regarding correlations. Moreover, central and western Nebraska contains one of the finest Pleistocene faunal records in America because the Pleistocene animals were crowded into this area by the advances of the continental glaciers on the east and northeast and the advances of mountain glaciations on the northwest and west. Nebraska paleontologists are following precise stratigraphic practices in the collection and study of these faunas, and their assistance has been of inestimable value.

The 1935 classification of the Nebraska Pleistocene by A. L. Lugn has been continued in the present study although some minor modifications have been made. The cyclic nature of Pleistocene deposition has been recognized, and it furnishes a valuable tool for use in close stratigraphic study. A complete Pleistocene cycle, in our opinion, involves erosion followed by coarse alluvial deposition ahead of the advancing ice, till deposition within till borders, and continuing coarse alluvial deposition outside of till borders, erosion followed by coarse alluvial deposition within the till borders during retreating ice, fine-textured alluviation in valley areas coincidental with aeolation in upland areas, closing with soil development. The Nebraska Pleistocene can be divided into six or seven cycles, some of which are complete while others are only partially represented (Fig. 1).

Two new names have been added since the 1935 work of A. L. Lugn: the Bignell, after Schultz and Stout, which is late Tazewell-Carey in age, and the Crete, which is assigned to the Illinoian. The Bignell is a fine-textured formation similar to the restricted Peorian but younger. It occurs extensively in moderately low terraces along the principal valleys but is generally very thinly represented in the upland areas, except locally where conditions were especially favorable for loess accumulation

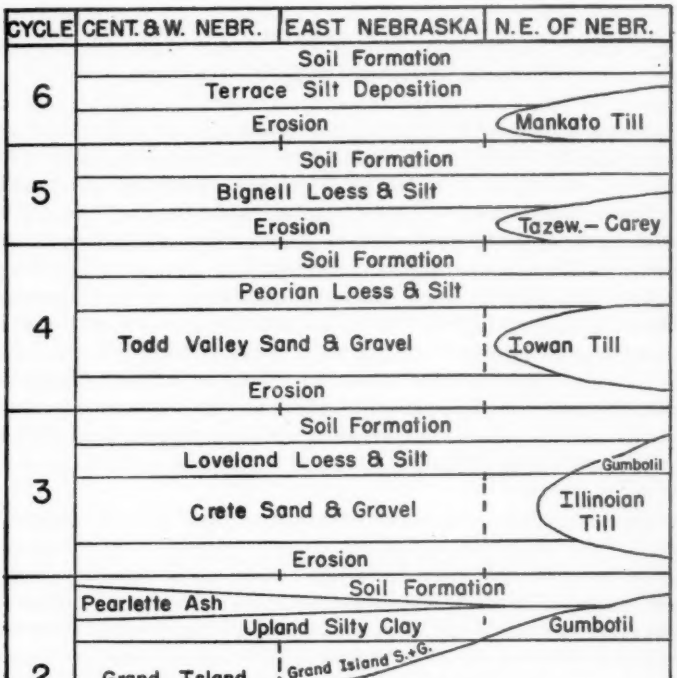

FIGURE 1.—*Cycles of the Pleistocene in Nebraska*

and preservation. The Crete is a new name to replace the interval which Lugn referred to as the valley phase of the Loveland. We believe it to be pre-Loveland and therefore not a true valley phase of the Loveland. It represents the coarse alluviation part of the Illinoian-Sangamon cycle.

We recognize both valley and upland phases of our Pleistocene formations and, in some cases, colluvial or side-slope phases. Many differences of opinion as to the mode of origin of the Loveland, Peorian, and Bignell formations arise from the fact that these formations are represented by upland phases which are true loesses and

valley phases which are largely water-sorted. Some of the coarse-textured formations are represented by relatively thick sands and gravels in their valley occurrences equivalent to thin lag-concentrate upland phase deposits. This is especially true of the Crete.

Physical evidences of unconformity and buried soils are used to separate contiguous formations. Buried subsoils, although not always recognized as such by some geologists, are even more effectively used than buried surface soils because they are more often present where the surface soils have been removed by erosion. We believe that the red color of the Loveland formation is not necessarily a function of source material but that the entire formation in many upland, well-drained occurrences is a part of the soil profile, the red color having developed as a result of a long period of soil development.

Subsurface work has shown that the pre-Pleistocene drainage pattern in Nebraska is distinct from the present pattern and that the pre-Pleistocene valleys were in existence along essentially the same lines in late Tertiary times. We recognize the Seward formation, an eastern fine-textured equivalent of the Ogallala, occurring as buried valley-side remnants in eastern Nebraska. The Seward, insofar as we now know, is limited to the subsurface in eastern Nebraska and shows a definite textural transition into the coarser-textured Ogallala formation westward. The pre-Seward and pre-Pleistocene surfaces were greatly influenced by the nature of the Cretaceous and older bedrock. Thus we find buried hogbacks, dip slopes, and water gaps in the harder Cretaceous formations and broader, flatter areas developed on the softer formations.

The present valley system began to develop in late Kansan time with the retreat of the Kansan ice, and many of these valleys were reopened time and again during middle and late Pleistocene.

We recognize a number of surfaces in our present topography, and some of them are terrace levels. Level No. 6 is the buried Kansan till plain in eastern Nebraska and the buried Grand Island sand plain in central Nebraska. No. 5 is the buried or mantled Loveland terrace which is shoulderlike in configuration. No. 4 is the Iowan terrace level, No. 3 the Tazewell-Carey level, No. 2 is late Wisconsin (probably Mankato), and No. 1 is very late Wisconsin to Recent.

The relationships of the post-Kansan till formations at the famous Harrison-Monona County line exposure northeast of Little Sioux in northwestern Iowa, where vertebrate fossils were collected and originally assigned to the Aftonian, have been restudied. These deposits are now known to be late Kansan and should not be regarded as representative of the earliest Pleistocene.

In conclusion we believe that the Broadwater fauna of Schultz and Stout and the Sand Draw fauna of McGrew both occur in deposits which represent the Nebraskan-Aftonian cycle, that they can be traced eastward and southeastward into the Holdrege and Fullerton formations, that the Holdrege sand and gravel is Nebraskan in age as its lower part can be traced under the Nebraskan till into the David City sand and gravel, and that the Fullerton formation can be followed from its type locality into the Aftonian silts between the Nebraskan and Kansan tills. The Broadwater and Sand Draw deposits are definitely post-Ogallala in age and rest on Ogallala or older

sediments with much greater unconformity than is apparent in any of the younger deposits.

The Pearlette ash is one of the finest markers in Nebraska and adjoining States as it is apparent that there was but one ash fall in our Pleistocene and that this material represents an instant during the deposition of the Upland formation and prior to the erosion interval which immediately preceded Crete sand and gravel deposition. The accurate reference of middle Pleistocene faunas to the Pearlette ash permits exact stratigraphic placement of many excellent faunal records.

GEOLOGY OF THE BLANCO BEDS OF WEST TEXAS

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The purpose of this paper is to present briefly the available geologic evidence bearing on the age of the Blanco beds in Crosby County on the High Plains of west Texas.

There are two separate localities of outcropping Blanco beds in Crosby County. The first, and best known is at the junction of the valleys of Crawfish Draw and White River, about 10 miles north of Crosbyton. The second locality is about 6 miles east and north of Crosbyton on the east slopes of White River Canyon. The maximum outcrop width in the first locality is about 2.5 miles and in the second locality about 1.5 miles.

The Blanco beds form rather conspicuous outcrops, due to the contrast of their light gray color with the bordering reddish-brown Cenozoic strata. Even so, they are so limited in their areal distribution that it is doubtful whether they would have been described separately if it had not been for the discovery of the distinctive fauna they contain, and for the belief that they were a fossiliferous phase of more widespread plains deposits.

Among the earlier workers who studied the Blanco beds were Cummins, Gidley, and Matthew. These men, although differing somewhat in their interpretation of the origin, all believed the Blanco beds to be of the same age as the upper section of bordering reddish-brown sands and clays. Cummins believed that most of the Cenozoic beds, including the Blanco, had been deposited in an "inland sea" or lake corresponding roughly in size to the area of the present High Plains. He did not attempt to subdivide the Cenozoic, and his Blanco beds are practically a synonym for what is now known as the Panhandle formation, which includes all of the plains Cenozoic in Texas except Recent surface sands. Gidley interpreted the Blanco beds to be a valley deposit in one of the aggrading stream valleys which had built up the alluvial apron of the plains during the upper Tertiary. He delimited the area of the Blanco to a section along the White River valley and the eastern plains escarpment, an outcrop distance of 15 or 20 miles. Matthew also believed the Blanco to be a stream valley deposit, but thought that the light-gray fossil-bearing strata, which are now known to be Blanco, were only a channel facies which interdigitated with the bordering reddish-brown Pliocene sands and clays. He regarded the reddish-brown deposits as a flood-plain facies of the Blanco. The belief that the Blanco was interbedded and contemporaneous with the widespread Cenozoic deposits, which were known to be mainly Pliocene, may have influenced Matthew in assigning the Blanco to the Pliocene.

During the past several years Grayson Meade and the writer have made field studies of the geology of the Blanco beds and the surrounding Cenozoic deposits. The results of this work have demonstrated that the Blanco rests unconformably on, and is appreciably younger than, the bordering reddish-brown Pliocene beds and was deposited in lake basins of comparable area and depth to the larger partially filled playa basins now existing in the same general region of the plains. The evidence for these conclusions has been discussed by Meade (1944) and by Evans and Meade

(1944). To review briefly: The lines of evidence indicating a lacustrine origin for the Blanco are: (1) The sediments are, in general, finer-grained in the middle and deeper parts of the section and coarser in the shallower marginal facies. This agrees with the conditions found in the modern lakes and is the reverse of the sedimentary conditions to be expected in a stream valley. (2) The deposits are well stratified and contain such typical quiet-water deposits as bentonitic clays, fresh-water sandy limestone, and local beds of diatomaceous earth. (3) The clastic materials, except for the bentonitic clays, are derived from quite local sources. This is in contrast to the stream deposits of the underlying Pliocene, which contain abundant pebbles derived obviously from distant sources. (4) There is no evidence of a continuation of a filled valley, such as was postulated by earlier workers, either between, above, or below the exposures of the Blanco beds, even though the canyons of White River and its tributaries and the eastern plains escarpment would almost certainly intersect such a stream course.

The reddish-brown deposits underlying the Blanco beds consist of two well-defined stratigraphic units separated by unconformity. As determined by vertebrate fossils, the lower unit is of early Pliocene age, and the upper unit of middle Pliocene age. A prominent caliche cap rock at the top of the middle Pliocene unit evidently formed at or near the surface of the Pliocene plains after deposition. There appears to be no reliable means of estimating the time required for the development of such a caliche horizon, although one suspects that a considerable time was involved. Quite surely there has been no comparably extensive development of caliche on the Texas plains during the Quaternary.

The basins in which the Blanco beds were deposited formed after the development of the caliche cap rock on top of the middle Pliocene plain. This is proven by abundant boulders and pebbles of the cap rock caliche which extend down the marginal basin slopes from the cap rock horizon and are incorporated into the basal member of the Blanco section. There is no direct evidence on the causes of the basin development, but it may be assumed that the basins were formed by some or all of the processes which were responsible for the formation of the late Pleistocene basins in the region. These processes include deflation, solution, and subsidence. The late basins, like those of the Blanco, cut down into and in some cases through the older Cenozoic section. It is not possible to do more than speculate on the time required for the Blanco basins to form.

The Blanco beds must have been laid down in an almost continuous process in permanent or nearly permanent water, as there are no discernible breaks in the sedimentation except for very minor erosional unconformities near the top of the section. Grayson Meade, who studied the Blanco fauna, which was obtained from different levels in the section, found no differences in the faunal aspect of the lower and upper levels. In both of the Blanco basins the lacustrine deposits accumulated to an average thickness of between 50 and 70 feet. Following the deposition of the Blanco beds there was a period of wind erosion which resulted in scouring and the partial deflation of the upper Blanco members. Overlying this wind-eroded surface is a mantle of wind-blown sands and silts which make up the surface of the present-day plains.

The geologic considerations which have an important bearing on the age of the Blanco beds are: (1) After the completion of development of the alluvial plain in middle, or perhaps upper middle, Pliocene, there elapsed a period of time of nondeposition during which climatic conditions were dry enough to favor the development of an extensive caliche zone near the plains surface. At some time following the caliche development, basins which were later to contain the Blanco lakes were formed to depths of at least 60 or 70 feet. If deflation was an important factor in the formation of the Blanco basins as it was in late Pleistocene basins of the region, this also requires the assumption of a dry climate and an appreciable period of time. (2) The essentially unbroken sequence of lacustrine strata making up the Blanco beds indicates deposition in permanent or nearly permanent bodies of water for a period of time long enough to accomplish the filling of the basins. Such permanent lakes are most logically explained as having resulted from a sustained period of moist climatic conditions. (3) After the Blanco basins were filled to a level approaching that of the surrounding plains, a return of relatively arid conditions is indicated by a windscoured erosional surface on the Blanco beds and by deposits of loesslike dust, unaltered volcanic ash, and unstratified surface sands. The Blanco beds evidently represent a period of relative humidity preceded and succeeded by periods of relative aridity. This condition suggests a glacial stage, and the faunal evidence precludes any but the first glacial as the time of the Blanco deposition.

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DISCUSSIONS

I. BEGINNING OF THE PLEISTOCENE IN EASTERN UNITED STATES

DR. ARTHUR BEVAN: I would like to ask Doctor Flint if he thinks it possible to develop any evidence criteria by means of which we could correlate the Cordilleran glaciation in the Rocky Mountains with the glaciation of the Plains.

DR. FLINT: It seems to me that the one critical region for that work lies at the base of the Rocky Mountains in Montana. When the work which the Geological Survey is now doing under the Missouri Valley project carries the correlation of the drifts from Iowa through the Dakotas and Montana to the base of the Rocky Mountains, and carries it into the Rocky Mountain drifts, which are there well displayed, we may have the answer to your question.

DR. ELIAS: I believe that we should not overlook, in our attempt to draw the boundary between the Pliocene and the Pleistocene, the desirability of having a uniform criterion in differentiation of the major units of geologic time. Now, this problem may seem academic in the area of great glaciation, where the difference between the Pleistocene and the Pliocene is pronounced, especially when the Pleistocene lacks the lowermost members. But the problem is complicated and becomes really difficult where, as in the High Plains, we do have the very earliest Pleistocene present. That is the unit which we agreed at a conference not long ago to call Blancan, leaving somewhat unsettled the problem whether to add it to Pliocene or to Pleistocene. It is in this area that I believe we should try to use the criterion of diastrophism as the ultimate basis for correlation and base on it the definition of the beginning of the Pleistocene period.

While I agree with Doctor Flint that the change of climate is an important factor in differentiation of Pleistocene from Pliocene, in the area where we have continuous sequence of beds we should apply the principle of diastrophism and try to recognize a major earth movement as the real indication of the beginning of the Pleistocene.

DR. FLINT: I think that, if we were to follow the conventional proposal which Doctor Elias has just made, we should first have to be sure that diastrophism is an adequate basis for differentiation of epochs earlier in geologic time. I do not believe that is an established fact and I feel quite sure that that criterion is unworkable so far as the Pliocene-Pleistocene sequence is concerned. If we adhere to the book, even granting the book is right, which I don't admit in this case, we will get very little further than we have got already. I believe we have to use something else, and that something else, it seems to me, is logically climate.

DR. ELIAS: I will give an example which really implements my statement. When I made probably a very inadequate attempt to build up a periodic system of the geologic periods of time, I realized that we use different criteria in differentiation of the Carboniferous from the Permian from those that we use in differentiation of the Tertiary from the Pleistocene. It is an established fact now that the major glaciation, which not so long ago was considered entirely Permian, is well down in the Carboniferous. Consequently, we cannot use the great glaciation of the end of the Paleozoic as a criterion for drawing the line between the Carboniferous and the Permian. Perhaps it is our anthropomorphic inclination to attach so much importance to the great Cenozoic glaciation, because it started mankind on his way, but by comparison with the similar situation at the end of the Paleozoic we are all wrong in attaching to the beginning of glaciation an exaggerated significance of a systemic or periodic boundary.

DR. BEVAN: I think Doctor Elias in his remarks has brought out what was in the back of my mind when I asked my question. Climatic change is all right, but I have long wondered if the Pleistocene didn't start in the Rocky Mountains long before it did in the interior of the United States.

Carrying Dr. Elias' remarks one step further, I think some of those who are authorities on the subject rather feel that mankind had to start in the Pliocene rather than in the Pleistocene.

DR. FLINT: I believe I mentioned in my talk that the unconformity, as it were, between the warm climate and the first cold climate is the thing that, as far as the glacial deposits are concerned, couldn't be contemporaneous. It could not be a time line. And I fully agree with you that glaciation began in the Rocky Mountains long before it did in the Central Lowland. But we have plenty of precedents for my point of view, because every one of our basal marine horizons bears exactly the same time relation to the deposits themselves as the one you have outlined.

So far as man is concerned, I think perhaps some of our paleontological friends might say man began even before the Pliocene.

II. THE AGE OF THE BLANCAN FAUNAS

DR. HORACE ELMER WOOD, 2ND: Having been one of the wild-eyed young radicals a few years ago, I find it a healthy experience to see some of my friends now shooting at something that we old fogies then proposed! It might be worth while to explain briefly why the 1941 committee report (*Nomenclature and correlation of the North American continental Tertiary*), which several of the speakers used as a point of departure, was as it was in relation to the present discussion.

The 1941 report was planned specifically to set up a North American provincial continental standard on the theory that we had got into a snarl by trying to assign more exact intercontinental correlations than were yet possible, and that our information here in North America was sufficiently good so that we could get further if we cut ourselves loose from an impossibly involved terminology and the irrelevant controversies that were associated with it. That this report has served one purpose is shown by the fact that everybody this morning has been able to make it clear what he meant when talking about the "Blancan", whereas, without that set of provincial age terms, several of the speakers would almost necessarily have fallen over their own terminological feet, or, at least, have left the audience in doubt as to their meaning.

In one of the early drafts of the report we side-stepped the intercontinental correlations involved in drawing boundaries between the epochs. Some of our critics convinced us that it might be useful to indicate where we thought the boundaries were. In the text, we specifically disclaimed any information as to where the "real" epoch boundaries were, and in fact disclaimed belief in the existence of such "real" boundaries. I disbelieve, completely, in the universal coincidence of diastrophism, or anything of that kind. When there appears to be a natural boundary between adjoining time units, it represents simply a gap in our information. As we have seen in the past history of geological progress and as was shown by Doctor Hibbard, all that is needed is more work and more collecting in the right places by competent men, and eventually the gap is filled. Somebody took me to task for drawing the Pliocene-Pleistocene boundary between the Benson and Curtis Ranch local faunas, and said, "Isn't that a pretty small gap in time, and there is no evidence of any diastrophism," and I agreed heartily. In other words, the more complete the evidence, the more any boundary line is going to be arbitrary. But if we find it convenient, and not too shocking by the European standard, it certainly is possible to move the Blancan across that largely verbal boundary.

Another bit of ancient history may be of interest. The committee did discuss the problem of the Blancan, and we were aware of reasons for placing the Pliocene-Pleistocene boundary at an earlier time, although much more evidence has been presented since then. There were several reasons for drawing the line where it was drawn, but probably the decisive one was our feeling at the time that students of the problem would not stand for lowering the boundary. Obviously, on the basis of the faunal change, the boundary can be drawn either before or after the Blancan. I agree that the Blancan represents a much shorter time than the Hemphillian, and that evolution can be traced *in situ* during the Hemphillian. Certainly, there is no evidence of it during the Blancan. Transferring the Blancan to the Pleistocene, therefore, would move considerably less than a third of the present Pliocene into the Pleistocene. Necessarily, if we are using the classical epoch terms, we must pay some attention to their boundaries as they were set up in Europe. It would be very nice if the most convenient boundary in Nebraska (the top of the Ogallala cap rock) happened to coincide with something that could be established as the legitimate demarcation in the European succession. It doesn't necessarily follow, and it would almost certainly be coincidental, if such were the case. Similarly, as a specialist on the fossil rhinoceroses, my ego would doubtless be flattered by having the Pliocene-Pleistocene boundary conform to the post-Hemphillian extinction of the rhinoceroses in North America; but there is no intrinsic reason why the Pliocene-Pleistocene demarcation in Europe should agree with this particular extinction, especially as the European rhinoceroses completely ignored the Pliocene-Pleistocene boundary, wherever it be drawn. Most of us here are not competent to speak with full conviction on the question of European correlation. Perhaps there is no convincing reason against transferring the Blancan across the boundary, but the case certainly needs to be presented in detail, rather than argued as a question of local convenience.

I might mention one point against the transfer of the Blancan to the Pleistocene. Although the Great Plains Blancan deposits show no special gap, geologically speaking, with the succeeding undoubted Pleistocene, there has been an amount of elevation and erosion since the deposition of the

Idaho Blancan (Hagerman) which we have been accustomed to consider as much less likely to be associated with a Pleistocene than with a Pliocene deposit.

We deal with progressively shorter time units as we approach the present time (compare the Blancan or even the Hemphillian with the Wasatchian), yet we unconsciously transfer to these short units concepts that perhaps apply to the Lipalian Interval. Thus we get an attempt to decide when the Pleistocene ended (if it has yet ended) as if we could expect to date its end by some event comparable to the Appalachian Revolution—which, of course, lasted many times as long as the whole Pleistocene.

DR. HIBBARD: There is one remark that I would like to make in regard to the *Nannippus* reported from the Pleistocene of Iowa. I have examined the specimen taken from the glacial deposits in Iowa. It is a tooth of *Nannippus gratum*, the same as the tooth of *Nannippus* taken from the Laverne deposits of Oklahoma. It is in no way related to the Blancan or Pleistocene problem. The reason for its occurrence in the Pleistocene deposit is speculation, but without doubt during the Pliocene many thin deposits containing vertebrate fossils were laid down in Iowa and the region to the north and east. These deposits were eroded away or moved by the ice during the Pleistocene, and the tooth became included in the younger deposits. The same accounts for the occurrence of Cretaceous vertebrates in glacial and nonglacial deposits of Kansas.

In regard to the specimens of *Nannippus* from Missouri, I have been unable to examine these. It appears questionable whether the Missouri specimens are Blancan in age.

DR. FLINT: I would like also to add one little thing about the *Nannippus* from Iowa. The question was raised—if this material was not indigenous to the drift where it was found, where did it come from? I am not so sure that all of the Pliocene alluvial deposits made in the eastern part of the plains have been removed by erosion. The work that was begun in South Dakota last summer shows that late Pliocene deposits occur quite far east in South Dakota, and I don't see why it might not be possible that remnants were buried in Iowa.

Another point that I would like to speak of in connection with Doctor McGrew's remarks is this. He spoke of a rodent indicating warm climate in the Rexroad formation in Kansas. I would like to ask why the particular zone in which those rodents occur might not have been Aftonian, a time early in the Pleistocene when conditions were presumably warmer by a considerable degree than they are at the present time, and possibly quite comparable with conditions we might have expected in that region in the Late Pleistocene.

DR. McGREW: The Rexroad rodents do not necessarily indicate warm climate, but the fact that there are no cold-climate rodents suggests that warm conditions prevailed. To elevate the Rexroad to Aftonian would mean to elevate all of our Blancan faunas. This would leave us without a fauna for the period between the beginning of ice formation and the climax of Nebraskan glaciation. When I described the Blancan fauna known as the Sand Draw I called it Aftonian because the invertebrates, according to the late Doctor Baker, could not have lived during a time of advanced glaciation. I did not take into consideration the fact that reasonably warm conditions probably prevailed in Kansas and Nebraska during the advance of Nebraskan ice and that these animals would not be driven out until near the climax of this ice advance. The Blancan faunas may have carried on into the Aftonian, but I rather think that Nebraskan glaciation put an end to the Blancan characteristics of the fauna.

DR. R. A. STIRTON: If we employ the Old World time terms, I think first we should know exactly the definitions and type sections as given by Lyell.

In 1833 when Lyell and Deshayes first divided the Tertiary deposits into a chronological series of formations, they introduced the terms Eocene, Miocene, Older Pliocene, and Newer Pliocene as convenient terms of expression in discussing the "periods" or epochs with which they were dealing. The type section of the Older Pliocene was the sub-Apennine strata in northern Italy. This included the marine Astian and the continental Val D'Arno (Villafranchian). The type section of the Newer Pliocene was the later marine Sicilian along the coast. In 1839 Lyell proposed the name Pleistocene and gave as its type the Newer Pliocene or Sicilian. The Pliocene then was restricted to his Older Pliocene or Astian. Then in 1873 in attempting to correlate his terminology with the work of Edward Forbes (1846) on *The geological relations of the existing fauna and flora of the British Isles*, Lyell suggested abandoning the name Pleistocene to avoid confusion because Forbes had actually used it for post-Pliocene instead of Newer Pliocene time.

Mr. Stout agrees in a close correlation of the Villafranchian and the Blancan as does nearly everyone who has looked at the evidence. If, then, we accept the type of the Pliocene as it was designated by Lyell, the Blancan is Pliocene. The boundary between the Pliocene and Pleistocene would fall very close to the position proposed by Doctor Hibbard and by most earlier workers.

MR. STOUT: With regard to the type definitions of Lyell, it may be of interest to mention a most important diagrammatic section of the Subapennine Hills of northern Italy which occurs in the recent comprehensive textbook on stratigraphy by Gignoux (*Géologie stratigraphique*, 3d ed., Paris, 1943). This diagram* is the clearest demonstration of stratigraphic relations at this famous locality that we have seen. It shows the traditional European terminology of these deposits. The "Older Pliocene" includes the Plaisancian and Astian sediments, with a supposed Pontian equivalent at the base, overlain by the "Newer Pliocene" or Villafranchian-Calabrian sediments. The Pleistocene was named as a substitute term for the "Newer Pliocene", and the Pliocene was restricted to what had been called "Older Pliocene". The Subapennine Hills area is the type locality of this "Older Pliocene", or Pliocene in its restricted sense.

The Plaisancian and Astian have been shown by Gignoux (1913) to be partially contemporaneous, with the Astian an overlapping facies. All of the authorities (as Denizot, 1938) agree that the classic deposits at Montpellier, near Marseilles, in southern France, are chiefly Astian, but recognize Plaisancian as present in the same area. The fossils from these beds appear to us to be mostly of Upper Ogallala type, whereas we regard the fossils of the Villafranchian to be similar to those of the Broadwater deposits of Nebraska. The marine facies of the Villafranchian is the Calabrian, but only the Villafranchian continental facies is present along this part of the French coast. The Villafranchian mammals include the short-jawed mastodonts related to the American *Stegomastodon*, and the *Plesippus* (or *Equus*) *stenonis* horse. This horse is very close to the American form, as pointed out by Dr. J. R. Schultz some years ago, and as may be seen by examining Schaub's recent photograph of the restored skeleton. In using fossil mammals for correlations of this type, approximate synchroneity rather than just homotaxiality is to be emphasized; that is why fossil mammals are usually such good "index" fossils.

DR. McGREW: I would like to remark that I think probably the crux of the whole problem is agreement on a workable definition of the Pleistocene in general terms, not necessarily stratigraphic terms or faunal terms. How are we going to determine what constitutes the beginning of the Pleistocene? That question has not been answered either in North America or in Europe. Are we going to regard the change of conditions that permitted ice to accumulate—whatever those were, perhaps diastrophism—as the dividing line between Pliocene and Pleistocene? It appears that this change of conditions can be correlated with elevation of the continents, sharp faunal change, the beginning of glaciation and probably definite stratigraphic changes. In other words a new period of time is strongly indicated. But if the type Pliocene of Europe includes the early part of the period of glaciation can we use this natural dividing line? This is a question that must be answered.

DR. STIRTON: Pleistocene is a time term. It represents an equal amount and the same time in Australia, South America, Europe, or in any other part of the world. What criteria we should use in determining the length of Pleistocene time I am not prepared to say, but it seems at present that the vertebrate faunas offer the best evidence for intercontinental correlations of ages (= absolute time) in geologic time.

There are some interesting faunal interchanges between North America and Eurasia which seem to tie in the late Pliocene and Pleistocene faunas in the two hemispheres. If we accept the evidence from Recent mammals (mountain lion, beaver, microtines, weasels, elk) that a wide and rapid dispersal can take place without appreciable evolutionary change, we can make intercontinental correlations in the Holarctic realm on the basis of these faunal interchanges, at least within the ages of an epoch—*e.g.*, Blancan.

The beavers offer important evidence in this faunal distributional pattern. In North America the castoroid beavers evolved through a succession of genera with distinct dental patterns from the Upper Miocene *Monosaulax* to the Pleistocene *Castoroides*. The Middle Pliocene (Hemphillian) *Dipoides* of that line spread also into Eurasia but became extinct there at the end of that age. This

* This diagrammatic section is reproduced as Figure 3 of the paper by Schultz and Stout.

includes the Eppelsheim and Montpellier faunas of Europe. In North America the line continued into the Upper Pliocene (Blancan) with the genus *Procastoroides* and became extinct on this continent with the last survivor of the Pleistocene *Castoroides*.

The living beaver, *Castor*, evolved from late Miocene and early Pliocene forms, probably correctly referred to the genus *Chalicomys*. The first representatives of this line reached North America in the Blancan. *Castor* species with similar characters in the cheek teeth lingered on in Eurasia. Evidently parallel evolution took place in both the Old and New worlds with the Villafranchian castors like our Blancan castors, and the true Pleistocene forms from both hemispheres were alike in their dental characters. This evidence together with that from other members of the mammalian faunas seems to indicate rather clearly that the Villafranchian faunas of the Old World are the contemporaries of our Blancan assemblages in North America. Most mammalian paleontologists agree on this point.

It would seem to follow that the Villafranchian fauna in northern Italy (Val d'Arno) is Pliocene since it is part of Lyell's sub-Apennine type section. We, then, can hardly escape the conclusion that the Blancan is also Pliocene. I am not familiar with the evidence pointed out by Mr. Stout, but recent papers by Zeuner (1945) and Schreuder (1945) also support a late Pliocene age for the Villafranchian.

I concur with Doctor Wood that much of our quibbling over these boundaries is wasted effort. Unless we clearly differentiate between absolute time and rock-time terminology we cannot derive a consistent and logical conclusion. I feel, however, that Doctor McGrew has made an important contribution in directing attention to the contemporaneity of early glaciation and the Blancan faunas. O. P. Hay suggested it before (1923), and W. F. Barbat (1934) has directed attention to similar evidence in California.

Other large mammals, not mentioned by Doctor McGrew, which reached North America from the Old World in Blancan time, are *Odocoileus*, *Cervus*, *Chasmaporthetes* and *Castor*.

MR. STOUT: We would like to make this one further comment regarding the Lyell terms. It appears that there is some question as to what Lyell wrote concerning them. He defined the Pliocene originally as consisting of an "Older Pliocene" and a "Newer Pliocene", both with type localities. Then when he coined the term "Pleistocene" it was as a substitute only for the "Newer Pliocene", and he restricted the term "Pliocene" to what he had previously called "Older Pliocene". Therefore, the Villafranchian or Calabrian is Pleistocene by original definition since it is the "Newer Pliocene". Even if the "Glacial Epoch" concept be emphasized, it appears that these Villafranchian-Calabrian beds could still be included as part of the "Glacial Epoch", but by original definition they are *the* Pleistocene.

III. THE PLIOCENE-PLEISTOCENE BOUNDARY IN THE GREAT PLAINS

DR. M. Y. WILLIAMS: Years ago, Dr. G. M. Dawson (Royal Society of Canada Proceedings, vol. 8, pt. 4, 1890, p. 18) concluded that there had been an elevation in late Pliocene time of more than 2000 feet in western British Columbia. Dr. M. A. Peacock, whom I am glad to see at this meeting, went into this whole problem in considerable detail (Geol. Soc. Am., Bull., vol. 46, p. 633-696, 1935).

He concluded there was a regional emergence of 3000–5000 feet in the later Pliocene along the western coast of British Columbia. Included in that evidence is the fact that the Gulf of Georgia is still submerged to the extent of 1200 feet, and we can trace the channel of the Fraser River out the strait of Juan de Fuca down to at least 3000 feet. Of course conditions there are submarine, but that does not apply to the Strait of Georgia, itself.

Through the interior of British Columbia there are lake deposits of late Eocene to Miocene age. The ancestral Fraser River delta extends down to the vicinity of Bellingham, Wash., and is late Eocene or Oligocene. This delta formation is entirely on the continental side—that is, there are no marine fossils in it.

There are no perfectly identified Pliocene deposits anywhere in western Canada that I am aware of. There are some consolidated gravels in British Columbia that may possibly be Pliocene. There is an old land surface which Collier and Thom recognized in Montana, which extends to the Cypress

Hills, and I quite agree with them that it is probably Pliocene. It is 200 or 300 feet below the Miocene plain. Below that, later erosion has cut another 700 or 800 feet. All the way up the Alaskan Highway there are flat plateaus. In the Pine River Valley, B. C., a well drilled in 1940 went down 1000 feet in silt and fill, where that river is overdeepened.

Our country has not been investigated geologically as much as it deserves, but in my opinion it is evident that we did have a decided elevation late in Miocene time. There was a great depression during the maximum glaciation. We have a rise of the coast to the extent of about 700 feet since the passing of the ice that is well verified in marine deposits lying on the site of greater Vancouver, containing faunas of mollusks which Doctor Fraser says belong at about 300 feet of water. Their elevation now is up to 250 feet above the sea. We have old sea beaches in northern Vancouver up to nearly 700 feet. The conclusion is that we have had an elevation of about 700 feet, and we still have a submergence of, say, roughly 1500 feet.

DR. A. L. LUGN: I am in full agreement with the remarks of Doctor Atwood and with those of the gentleman who just spoke. Also, I would like to second the conclusions of Doctor Elias, and I would just make the remark that it is my considered opinion, without reviewing the evidence at this time, that deposition of the Ogallala caprock should be agreed upon and accepted as the end of Ogallala time and the end of the Tertiary period. All deposits which can be shown to be post-Ogallala caprock erosion in age should be regarded as Early Pleistocene. Though they may also be older than Nebraskan till, such materials as the David City formation, the lower part of the Holdredge formation, possibly the Blancan beds, and other equivalents in Nebraska, Kansas, and elsewhere belong to this category of very Early Pleistocene formations.

I think we are a little inclined to think of Ogallala or the Pliocene as ending simultaneously with the advent of Nebraskan ice, which is hardly probable since the ice has to originate far to the north and extend itself a great distance during a long time. There was time for much erosion and deposition of intermediate formations.

DR. SCHULTZ: We think that the only real discrepancy which we can see between the Nebraska and Kansas paleontological and geological evidence is that Doctor Hibbard claims that no mammoth or bovid remains have been found below the Pearlette ash in Kansas, while in Nebraska our main source of this type of material is from below the ash. We must "lick" this problem in Kansas and Nebraska (perhaps by another field conference) and come to a definite agreement before very much can be really contributed on this point.

We do agree with Doctor Frye's correlation charts of the Kansas Pleistocene which he showed here, and also with Professor Reed's, but it must be pointed out again that in Nebraska our chief Middle Pleistocene faunas (Hay Springs-Rushville-Gordon) are definitely from below the ash.

DR. HIBBARD: I would like to say that the problem, as pointed out by Doctor Schultz, is the big difficulty in the correlation of the later Pleistocene deposits in Kansas and Nebraska. In southwestern Kansas there is a definite sequence of faunas, and certain forms, such as *Bison* and *Paramylodon*, have not been found in these deposits to date, though the remains of these forms do occur in that region in younger beds. Remains of a small sloth have been taken from the Rexroad formation. The sloth is not *Paramylodon*. I think it is comparable to the sloth known from the Broadwater.

In Kansas there has been described the Rezabek fauna from Lincoln County, which appears to be comparable to the Hay Springs fauna of Nebraska based on the presence of *Microtus pennsylvanicus*, *Ondatra nebrascensis* and *Castoroides*. The beds from which these remains were recovered are channeled into the Meade formation of that area and are Post-Pearlette ash.

From a study of the Microtines occurring in the successive faunas in Kansas it has been found that they are the best fossils known at present to use in an attempt to correlate late Cenozoic deposits in that region. On the basis of this study and from field observations it appears that the terrace in Nebraska containing the Hays Springs and Rushville faunas is post-Pearlette ash. I consider the ash as belonging to an older deposit which forms, in many places, the High Plains level. The Cimarron River and its terraces are younger than the Meade formation, and they have been developed in these older deposits. It appears that the same condition exists in Nebraska and that these terraces have been developed in older deposits. Naturally due to the downcutting of the streams the younger terraces would be topographically lower than the older ash which occurs at a

much higher topographic level. As a rule, in Middle to Late Pleistocene deposits the youngest beds are the lowest in the geological section and when they occur as terraces many times they are channeled into older Pleistocene beds, and these terraces appear as a continuation of older beds.

MR. REED: I might say that what Doctor Hibbard says about the relative topographic position of successively younger Pleistocene deposits is true in some parts of Nebraska, but we do have both situations. In eastern Nebraska we usually find our older Pleistocene below our younger Pleistocene, but in western Nebraska their topographic relationship is reversed, by channeling such as he mentioned. We are definitely of the opinion that the "Hay Springs fauna" occurs in sediments underlying and older than the Pearlette ash but we hope to be able to solve some of these differences of opinion by drilling detailed profile sections away from upland areas where more complete sequences are present, into fossil locales so that we can prove definitely that it is or is not channeling. We hope to solve some of those problems.

DR. FRYE: For the most part, it is true that in the Kansas localities there is such a reversal as pointed out by Hibbard. Pleistocene deposits of younger age occur topographically lower than older Pleistocene. However, in a few localities, solution-subsidence or downfaulting has allowed accumulation of sediments in basins, and a normal upward stratigraphic sequence of sediment occurs. I believe we can't generalize about the topographic positions of younger and older Pleistocene sediments but rather must examine the local conditions.

SUMMARY AND CONCLUSIONS

BY EDWIN H. COLBERT

In our study of the Pleistocene period it is necessary, as Professor Flint has pointed out, to define the period, and especially to fix its beginning. This is a problem which at best is difficult, because different criteria exist for drawing up a definition of the base of the Pleistocene, and upon the basis of these different criteria, separately considered, different results will be obtained.

To arrive at a proper definition of the base of the Pleistocene sequence in any particular area, it is necessary to have a continuous Plio-Pleistocene succession of sediments. Such successions are not common, but they do exist; as for example the marine crag sequence in southern England and the marine sequence in southern California, as well as certain continental successions such as the Villafranchian sequence in Italy and the San Pedro Valley sequence in Arizona. If boundaries can be fixed upon the basis of successions such as these and extrapolations extended to other areas, it may be possible to achieve results of some degree of satisfaction. But in many areas the picture is complicated by local developments, or portions of the sequence are missing, so that a satisfactory solution of the problem, as least as applied locally, frequently is not possible.

In eastern United States the problem of interpretation of the Plio-Pleistocene sequence is complicated by the fact that no continuous succession of strata is at the present time recognized. This may be due in part to the fact that the sediments of the Atlantic coast region have not been completely studied. Suffice it to say here that there is needed a correlation of certain eastern North American marine sediments with continental facies.

Generally speaking, it can be said that the base of the Pleistocene sequence in eastern and central United States is to be defined by the appearance of the lowest glacial sediments. In the central area this means by the presence of the Nebraskan drift, and it is particularly true in those areas where there is no distinct break in the Plio-Pleistocene sequence. Therefore, by accepting the appearance of glacial deposits as indicative of the base of the Pleistocene we are accepting in fact climatic factors as the criteria for the definition of the opening of this geologic period. This may be objected to by some on the grounds that it is not uniform with our acceptance of other criteria, such as diastrophism, as the basis for dating the beginning of other geologic periods. Moreover, there is the recognized objection that owing to the time factor involved in the advance of the first glacial front criteria for the beginning of the period based upon glacial phenomena imply noncontemporaneous dates in various geographic regions, dependent upon their latitudinal position or upon their relative elevation. It is felt, however, that, in spite of these objections, the acceptance of glacial phenomena as indicative of the beginning of Pleistocene times offers a workable compromise that can be adhered to by most students of the Pleistocene.

In those areas, regions where glacial phenomena are not evident, in areas away from glacial fronts or from outwash plains for instance, it is evident that other criteria must be used and accepted for the dating of the beginning of Pleistocene times. The problem then is to try to correlate such criteria with established glacial evidence.

But, before this, there comes the problem of what criteria can be used in non-

glaciated regions for dating the beginning of the Pleistocene, and what value can be attached to these criteria. Naturally, faunal evidence is of particular importance. And, insofar as the problem at hand is concerned, the problem of the Pleistocene of the Great Plains, this brings us to the much-debated question of the Blancan faunas. These vertebrate faunas are now well known from various areas in the Great Plains region, and they have been described and compared with comparable faunas in other parts of the world.

The problem is this—Are the Blancan faunas representative of the last of Pliocene times or are they representative of the beginning of the Pleistocene? It is not an easy problem to resolve, even though the definition of the Blancan as a time unit has been established by committee and has been accepted by most workers in the field of vertebrate paleontology.

In the type area of Crosby County, Texas, the Blanco sediments consist of rather conspicuous but limited outcrops. These have been variously interpreted by Cummins as indicative of an "inland sea", by Gidley as a valley deposit, by Matthew as a stream deposit, and more recently by Meade and Evans as a playa lake deposit. The evidence for this last interpretation is that the Blanco sediments are fine-grained and stratified, they contain bentonitic clays, some limestones and diatomaceous earth, and, finally, the clastics are all of local origin. These facts, say Meade and Evans, point to a lacustrine origin for the Blanco type deposits. The lacustrine origin for the type Blanco beds in turn indicates a period of moist conditions which followed the preceding dry conditions typical of much of middle and late Pliocene times. Therefore, it is logical to think that the Blanco sediments represent the onset of a cool, moist, glacial stage, an interpretation that some authorities feel is justified by the faunal evidence.

What is the faunal evidence?

The Blancan faunas are characterized by the appearance of various new genera which lived not only through Blancan times, but persisted on through the extent of the Pleistocene period. Evidently there was a wave of extinction at the end of Hemphillian times, just before the opening of the Blancan, so that the appearance of these new generic types is particularly prominent. Then, after the close of the Blancan, many of the large, characteristic Pleistocene mammals make their appearance. The genera especially diagnostic for the Blancan are the horse, *Plesippus*, the dog, *Borophagus*, and the beaver, *Procastoroides*. Yet in spite of these faunal criteria—the wave of extinction preceding the beginning of the Blancan, the appearance of new generic forms in the Blancan, the presence of certain genera limited to the Blancan, and the appearance of many large typical Pleistocene genera after the close of the Blancan—the fauna as a whole is marked by many genera that persisted through from Hemphillian into post-Blancan times. So it can be seen that the problem is a complex one, a problem in which the various contributing factors must be weighed against one another, in order that a conclusion can be reached based upon the counterbalancing of several lines of evidence, with the proper emphasis given to each.

It can be argued, for example, that intercontinental migrations shown in the Blancan faunas indicate marked diastrophism and epeirogenic uplifts. And these are criteria that would be accorded great weight by some for regarding the Blancan as

an opening phase of the Pleistocene period. This argument would be in accord with the evidence for cool, moist conditions, cited above, as indicative of a Pleistocene age for the Blancan sediments and their contained faunas. Moreover, such diastrophic events, as revealed by faunal intercontinental migrations, can be reinforced by the evidence of a period of rejuvenation in erosion with the consequent formation of stream terraces in the central Plains area during Blancan times. This, it must be admitted, is the most profound change as revealed in continental sedimentation since the beginning of the Pliocene.

It should be pointed out here, however, that the terrace evidence within the Blancan is not as satisfactory as it might be. Deposits are discontinuous, and the correlation of the terraces has not been carried forward far enough to be truly definitive.

Still another line of evidence indicative of diastrophism within Blancan times is that afforded by the study of the Plio-Pleistocene transition along the Rocky Mountain front. Here we see a period of rejuvenation in stream cutting, as shown by the superposition of gorges through buried mountain ranges, and the denudation of the sedimentary mantle, immediately preceding the first ice advance down from the mountain heights.

Thus the evidence can be integrated—the evidence of faunas, of stratigraphy, of structural geology and of geomorphology. The picture resulting from this many-facetted study is that of a period of uplift, of increasing coolness, and of increasingly moist conditions. It is a picture of wide movements of mammalian faunas, of the appearance of new mammalian types, yet on the other hand of the persistence of many mammalian types from the preceding stages of the Pliocene. In other words, we see in the Blancan the setting of the stage for Pleistocene history; we see an intimation of things to come.

But has our question been answered? Do we yet know whether the Blancan is properly to be considered as of Pliocene or of Pleistocene age? Do we yet have valid criteria, beyond glacial evidence, for dating the beginning of the Pleistocene period? Indeed, is the glacial evidence, as founded on climatic changes, valid for dating the beginning of the period? Or should we rely rather upon diastrophism?

Generalizations are dangerous, but it probably is safe to say that there is a feeling among a majority of students working on this problem that diastrophism does not offer a consistent and wide-spread criterion for dating the beginning of Pleistocene times. The evidence is local, and indications would seem to show that diastrophism was not either world wide or of great magnitude during the Plio-Pleistocene transition.

Glacial evidence, based upon climatic factors, does, as pointed out above, offer evidence for a workable definition of the beginning of the Pleistocene sequence, where such evidence is to be had. But in many regions it is not to be had, and then reliance must be placed upon other criteria, particularly faunal evidence.

But here we run into the complication, in the Great Plains area particularly, that faunal evidence fails to show a sharp break in the succession, where the sequence is completely known. Differences can be seen, extinctions and the appearance of new forms can be traced, but many faunal elements persist through from the Pliocene into the Pleistocene without appreciable changes. Where, then, can the line be drawn?

It is a question to which an answer still is to be found. As said before, we are too

close to the events being studied for gaps to be apparent. The gaps that separate earlier geologic periods are largely the result of gaps in knowledge, rather than the existence of truly valid diastema between one series of geologic events and another. In the Plio-Pleistocene transition no such gaps exist, and we see what is nearer the real condition that must have held through geologic time. There is a continuous sequence of sediments and of animal life, and any line that is drawn must of necessity be to a large degree arbitrary.

What we know is this. The Blancan deposits and their contained faunas are of preglacial age, but they indicate a period of moisture and of cooling. The animals indicate a transition from the typical Pliocene to the typical Pleistocene faunas. These Blancan deposits and faunas can be correlated in every way with the similar Villafranchian deposits and faunas of the Old World. The question of their true age then is largely one of definition. If they are regarded as coming within the Pleistocene period, then the Pleistocene must be thought of as beginning before the actual advance of the ice. And the first appearance of glacial deposits represents not the base of the Pleistocene but some time line well within the sequence of the early Pleistocene. If, on the other hand, they are regarded as coming within the Pliocene period, then the Pliocene must be thought of as ending with a combination of conditions, structural, climatic, and faunal, that clearly foreshadowed what was to take place during Pleistocene times. Thus in this case the end of the Pliocene is quite unlike most of its duration. And the beginning of the Pleistocene can be regarded as being marked by the advance of the first continental glaciers.

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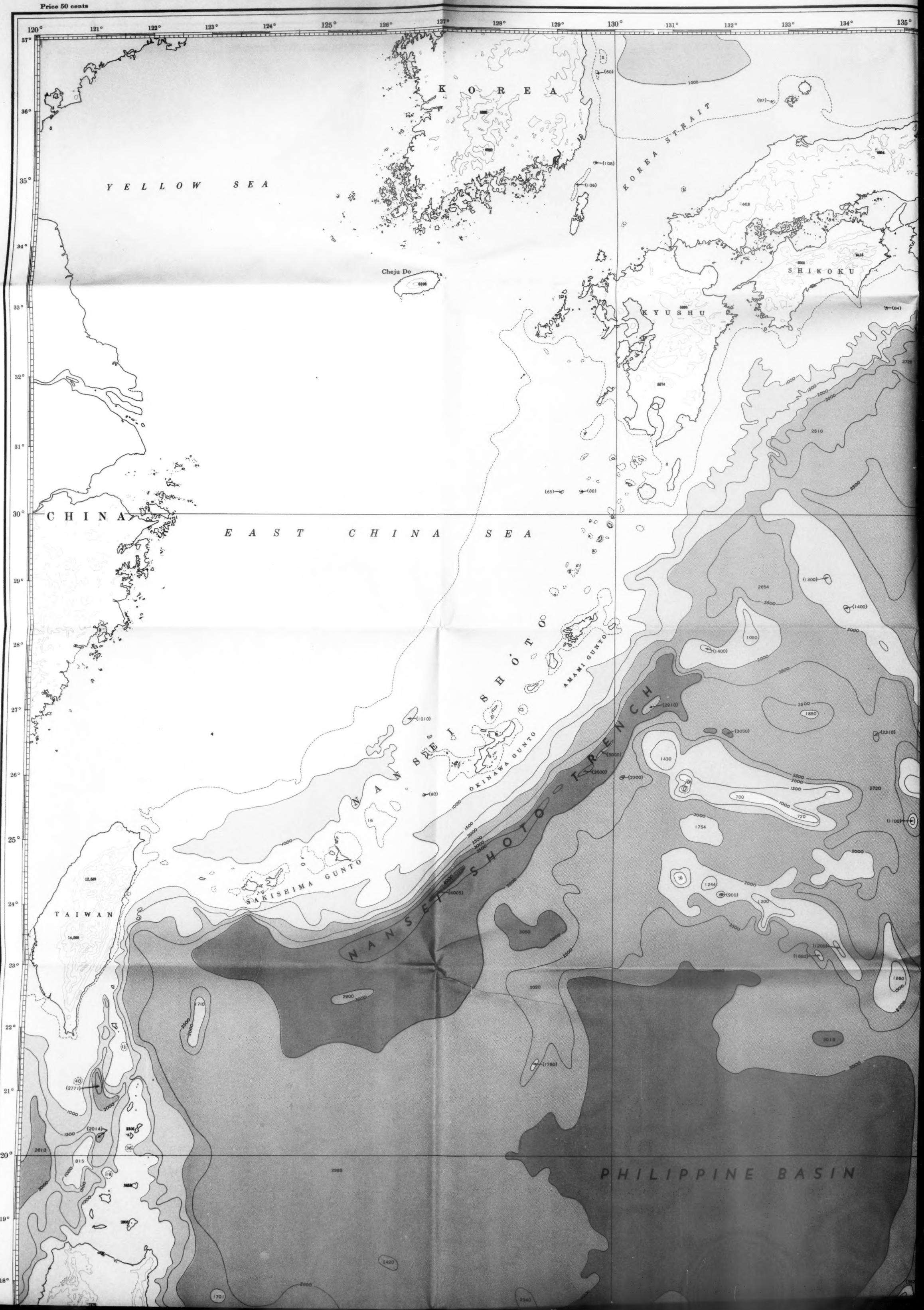

TECHNOLOGY DEPARTMENT

BATHYMETRIC CHART

KOREA TO NEW GUINEA

INCLUDING

THE PHILIPPINE SEA

Compiled mainly from data by the U. S. Navy to 1946

DEPTH CONTOURS IN FATHOMS
HEIGHTS IN FEET

Natural Scale 1: 4,075,440 at Lat. 16° 30'

HONSHU

NANPO SHOTO

IZU TRENCH

OGASAWARA GUNTO

Io Jima

KAZAN RETTO

BONIN TRENCH

MARIANAS TRENCH

Active volcano reported 1946

PHILIPPINE BASIN

PHILIPPINE SEA

LUZON

PHILIPPINE ISLANDS

MINDORO

PANAY

LEYTE

SAMAR

NEGROS

SULU SEA

MINDANAO

Jolo I

MANILA TRENCH

PALAU ISLANDS

Yap Island

Ngulu Atoll

WEST CAROLINE BASIN

HALMAHERA

Tables of the velocity of sound in pure water and sea water Table 2, Area 41
By D. J. Matthews, F. I. C.
Second Edition, 1939
British Admiralty, Hydrographic Department

Depth in fathoms	Mean Velocity fms./sec.	Correction	Depth in fathoms	Mean Velocity fms./sec.	Correction
100	837	+ 5	2800	824	+ 87
200	829	7	2900	825	91
300	823	9	3000	825	96
400	820	10	3100	826	105
500	819	12	3200	827	112
600	817	13	3300	828	116
700	817	15	3400	828	124
800	816	16	3500	829	132
900	816	18	3600	830	141
1000	815	19	3700	831	150
1100	815	21	3800	832	157
1200	816	24	3900	832	164
1300	816	26	4000	833	174
1400	816	28	4100	834	183
1500	816	30	4200	835	190
1600	817	34	4300	835	197
1700	817	37	4400	836	208
1800	818	41	4500	837	220
1900	818	44	4600	838	231
2000	819	47	4700	839	242
2100	819	51	4800	840	251
2200	820	55	4900	840	260
2300	820	59	5000	841	272
2400	821	65	5100	842	285
2500	822	71	5200	843	299
2600	823	75	5300	844	308
2700	823	80	5400	844	317
			5500	845	331

Corrections to be applied to observed soundings taken with sonic sounding apparatus calibrated to a standard velocity of 4800 feet per second.

PPINE BASIN

P I N E S E A

C A R O L I N E I S L A N D S

EAST CAROLINE BASIN

WEST CAROLINE BASIN

WEST CAROLINE TRENCH

YAP TRENCH

MARIANAS TRENCH

MARIANAS TRENCH

Saipan I

Tinian I

Guam

Sulphur boil reported 1965

Yap Island

Ulithi Atoll

Ngulu Atoll

Faraulep Atoll

Namonuito Atoll

Eauripik Atoll

PALAU ISLANDS

22°
21°
20°
19°
18°
17°
16°
15°
14°
13°
12°
11°
10°
9°
8°
7°
6°
5°
4°
3°
2°
1°

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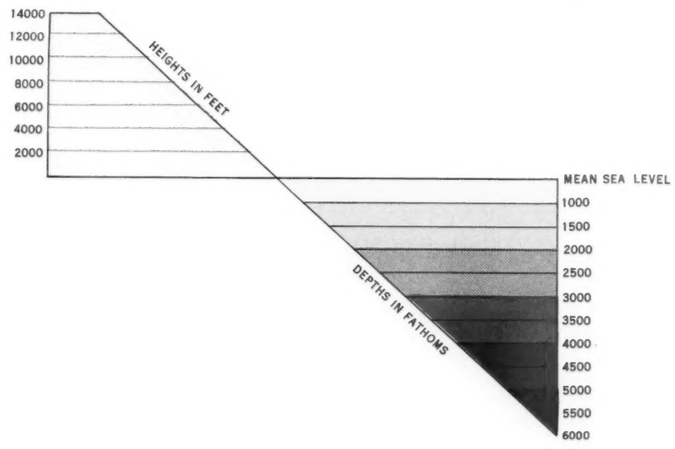

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CAROLINE ISLANDS

WEST CAROLINE BASIN

EAST CAROLINE BASIN

PALAU ISLANDS

WEST CAROLINE TRENCH

Yap Island

Ulithi Atoll

Ngulu Atoll

Faraulep Atoll

Eauripik Atoll

Namonuito Atoll

BIAK

GEELVINK BAY

NEW GUINEA

ADMIRALTY ISLANDS

Manus I

Mussau I

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